


STANDARDS RESEARCH

# Embodied Carbon Pathways for Canadian Residential Equipment

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# Executive Summary

Reducing carbon emissions is essential to meeting Canada's near- and long-term climate goals. While the operational efficiency of buildings has been a central focus, embodied carbon (emissions associated with materials, manufacturing, refrigerants, and equipment replacement) is emerging as a critical frontier for action. This research supports the development of Canadian standards to reduce the embodied carbon of residential equipment, a category that remains largely unregulated despite its growing contribution to building emissions. Further, this research identifies the importance of addressing both energy efficiency and embodied carbon reductions in coordination, optimizing emission reductions throughout the equipment life cycle.

Mechanical, electrical, and plumbing (MEP) systems, including heating, ventilation, and air conditioning (HVAC) equipment and appliances, can account for as much as 35% of a home's initial embodied carbon. Modelling based on CIBSE TM65, *Embodied carbon in building services: A calculation methodology* shows that refrigerant leakage during the use phase is the largest emissions source across all equipment types, even when using lower global warming–potential refrigerants. While comparisons often use different system boundaries, the evidence consistently shows that residential equipment contributes significantly to total building emissions and remains under-addressed in current standards.

The research identifies persistent data and methodological gaps across three impact areas: embodied carbon emissions, refrigerants and gas emissions, and equipment lifespan. Emissions data is often fragmented or absent, particularly for electronics and smaller appliances. Refrigerant leakage assumptions vary significantly across standards, reducing comparability. Service life is inconsistently reported, making it difficult to assess product durability and accurately account for emissions resulting from frequent equipment replacements. Together, these gaps hinder accurate life-cycle analysis and effective emissions reduction strategies.

This report evaluates these gaps and presents 15 targeted recommendations to integrate embodied carbon, refrigerant emissions, and service life considerations into residential equipment standards. Key priorities include:

- Developing a **national whole-building embodied carbon methodology** tailored to low-rise residential construction.
- Expanding **Product Category Rules and Environmental Product Declaration** coverage across residential product categories, with public oversight.
- Adapting and expanding **ASHRAE TM65NA, *Embodied Carbon in Building Services: A Calculation Methodology for North America*** for interim emissions reporting, covering electric and electronic equipment, and building a national database.
- Strengthening **refrigerant management regulations** and establishing leakage rate assumptions.
- Standardizing **reference service life reporting** and supporting product repairability, reuse, and recycling.
- Linking **energy efficiency, system sizing, and embodied emissions** to improve both operational and material performance.

By closing both data and regulatory gaps, Canada can enable more accurate emissions accounting, strengthen product standards, and support domestic manufacturers in meeting global low-carbon expectations. This work provides a road map to make residential equipment not just functional and efficient, but climate-aligned and future-ready.



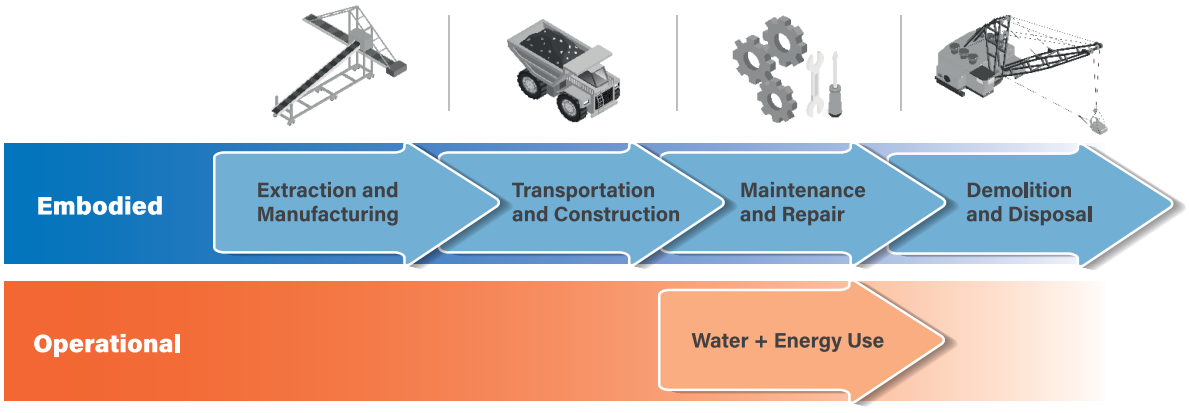
**"While many decarbonization efforts have focused on operational emissions—those generated by heating, cooling, and powering buildings—embodied carbon remains a significant and under-addressed source of emissions."**

## 1 Introduction

The built environment is a major contributor to global greenhouse gas (GHG) emissions, with impacts arising from the construction, operation, maintenance, and eventual decommissioning of buildings, as well as the full life cycles of the materials, systems, and equipment [1]. While many decarbonization efforts have focused on operational emissions—those generated by heating, cooling, and powering buildings—embodied carbon remains a significant and under-addressed source of emissions. Embodied carbon refers to the GHG emissions generated across a product's life cycle, including raw material extraction, manufacturing, transportation, maintenance, and disposal [1]. As illustrated in Figure 1, these emissions are distinct from operational emissions, which arise from energy and water use during a building's use phase, and occur across multiple life-cycle stages, from production through end-of-life.

**Figure 1: Embodied vs. Operational Carbon Through Life Cycle Stages**

*Embodied carbon refers to the greenhouse gas emissions generated across a product's life cycle, including raw material extraction, manufacturing, transportation, maintenance, and disposal*



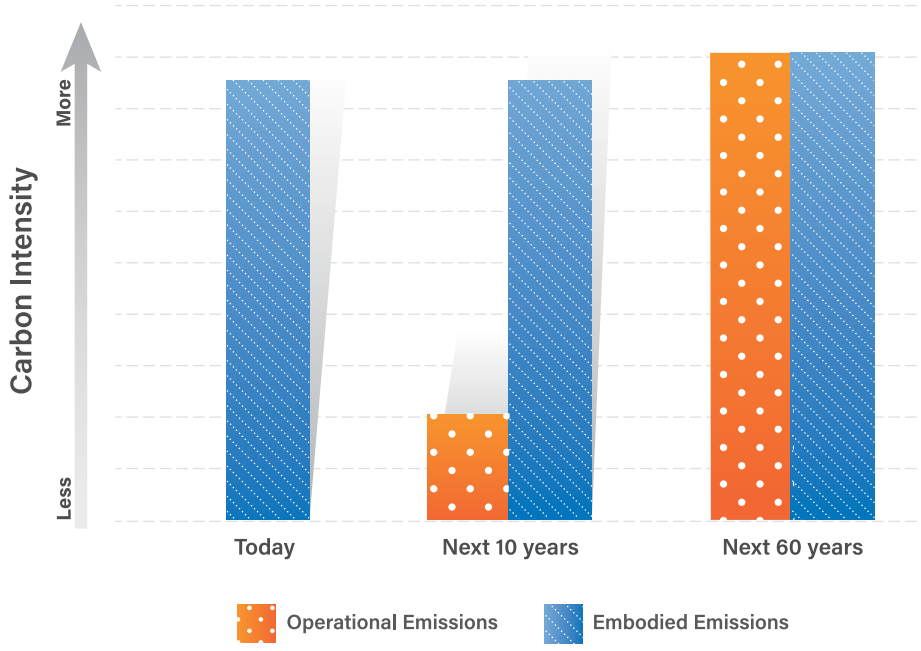
As buildings become more energy efficient and electricity grids decarbonize, operational emission intensities are decreasing, and addressing embodied carbon becomes essential to meeting long-term climate goals [2]. Unlike operational emissions, which are distributed over decades of building use, embodied emissions are front-loaded, occurring during the earliest stages of a building's life cycle. As shown in Figure 2, most embodied carbon is emitted before a building is even occupied, while operational emissions accrue gradually over time. This makes early action critical, because reducing embodied emissions has immediate climate benefits.

Regulation and market action in Canada have begun to address embodied carbon in buildings. Projects such as the Ontario Secondary School Teachers' Federation headquarters in Toronto and the University of British Columbia's Brock Commons Tallwood House demonstrate how mass timber and early contractor engagement can reduce the embodied emissions of structural systems [3]. A joint research project by Toronto Metropolitan University and RDH Building Science developed guidance to support lower-carbon enclosure strategies, while the City of Vancouver has introduced policies that set embodied carbon limits and compliance pathways for high-impact materials, such as concrete [4], [5].

Despite this momentum, residential buildings and the equipment that enables them to function remain largely excluded from embodied carbon reduction strategies, even though emerging research shows that residential equipment can contribute significantly to life-cycle emissions [6], [7], [8]. These impacts are amplified by short product lifespans leading to frequent replacement, and the use of emissions-intensive materials such as metals and refrigerants. Addressing equipment-related emissions represents an opportunity for meaningful reductions and is essential to achieving Canada's climate targets.

**Figure 2: Timing of Embodied and Operational Carbon Emissions**

*Embodied emissions occur upfront during a building's early life cycle stages, while operational emissions accumulate gradually over time. This front-loaded emissions profile underscores the importance of addressing embodied carbon early in the design and construction processes.*



National frameworks, such as the *Canada Green Building Strategy,* the *Canadian Net-Zero Emissions Accountability Act,* and the *National Research Council's (NRC's) Guidelines for Whole-Building Life Cycle Assessment,* provide a foundation for action [9], [10], [11]. These initiatives align with global best practices and support the development of standards that drive low-carbon equipment design while reinforcing Canada's leadership in sustainability and emissions management.

This research supports the development of Canadian standards and guidance to reduce the embodied carbon of residential equipment. It identifies adaptable existing standards, highlights gaps requiring new standards, and outlines strategies to update emissions accounting, integrate refrigerant and service life considerations, and align with international frameworks. By reflecting global best practices, including international life-cycle assessment (LCA) methodologies and circular economy principles, this work ensures alignment with evolving regulatory and methodological approaches.

Embedding emissions-focused approaches into equipment standards enables impactful actions, leading to measurable carbon reductions, promoting responsible resource use, and strengthening the global competitiveness of Canada's manufacturing sector. Harmonization with international frameworks ensures regulatory alignment and positions Canadian products for success in global markets. This research offers a pathway for standards that reflect the full life cycle of residential equipment and support a low-carbon future.

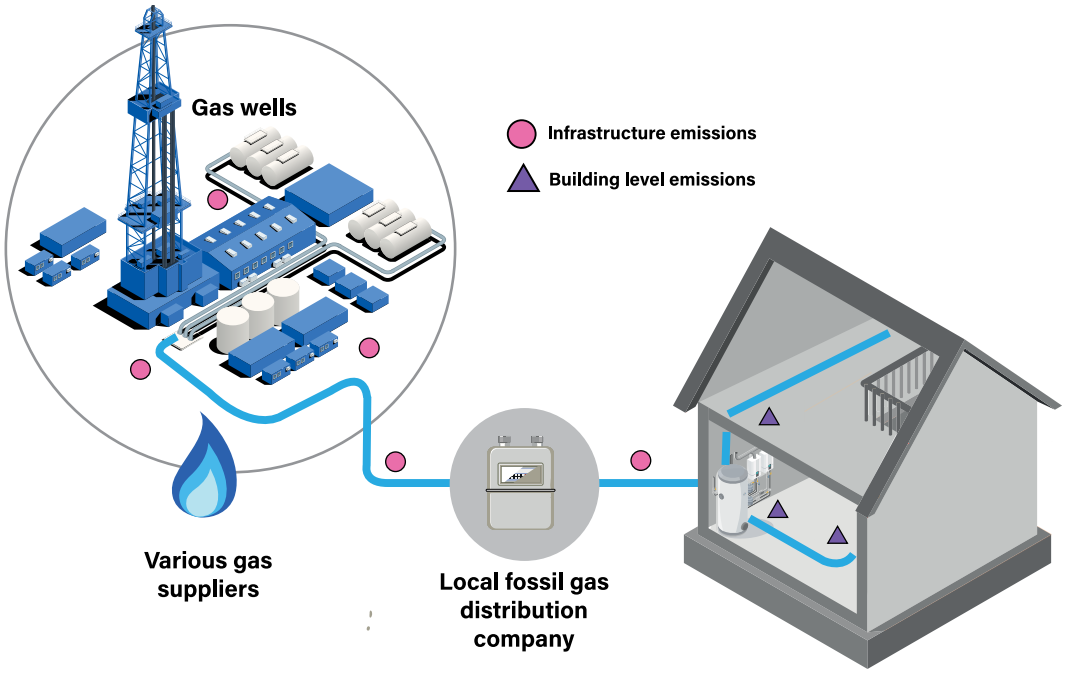
# 2 Methods

## 2.1 Scope and Boundaries

This study focuses on developing a framework for integrating embodied carbon into residential equipment standards. It adopts a whole life-cycle perspective and uses the building as the system boundary, which is aligned with EN 15978, *Sustainability of construction works,* to support consistency with building-level assessment practices. This includes emissions from

**Figure 3: System Boundaries for Equipment Emissions**

*Clarifying boundaries: this diagram distinguishes between infrastructure emissions (e.g., gas extraction, transmission, and distribution) and building-level emissions attributable to in-home equipment use. While this study uses the building as the system boundary, emissions resulting from upstream infrastructure remain an important context for equipment-related impacts.*



manufacturing, installation, use, maintenance, repair, replacement, and end-of-life stages.

Using the building as the boundary ensures comparability with whole-building LCA methodologies but introduces a key limitation. Figure 3 shows how emissions from upstream infrastructure, such as gas distribution leakage, fall outside the building boundary, even though they are a direct result of in-building equipment use. Additionally, while emissions throughout the LCA scope are covered in this research, in many cases, equipment embodied carbon emission data is only available and reported for the product stage (A1: Raw material extraction, A2: Transportation, and A3: Manufacturing). Both issues highlight the importance of clearly defined boundaries and coordinated reporting frameworks when developing emissions-focused standards for residential equipment.

## 2.2 Objects of the Study

The range of residential equipment included in the scope of this research spans heating, ventilation, and air conditioning (HVAC) systems, water heating units, household appliances, and electronics. Key equipment types include electric and gas storage water heaters, refrigerators, heat pumps, room air conditioners, and dishwashers. Additionally, smaller products, such as set-top boxes and battery-charging systems, are included to represent a broad analysis of residential equipment. A full list of the equipment in scope is included in Appendix A.

## 2.3 Analysis Methodology

The research followed a structured approach, beginning with data collection and concluding with a comprehensive analysis. The data collection methodology consisted of two primary components:

1. **Emissions Research** – Identifying and evaluating data sources that provide insight into embodied carbon emissions, refrigerant impacts, and lifespan considerations.
2. **Standards Research** – Investigating national and international standards to assess existing frameworks, identify gaps, and inform future standards development.

## 2.4 Data Collection

### 2.4.1 Standards, Tools, and Technical References

Standards that define emissions-reporting protocols, technical references that inform lifespan estimates and service assumptions, and tools used for embodied carbon and refrigerant impact analysis were referenced in this study, and those consulted but not cited directly in the main body of the report are listed in Appendix B.

#### 2.4.1.1 Standards

A selection of national and international standards informed this study's approach to emissions accounting, refrigerant management, and LCA. TM65.1, *Embodied Carbon in Building Services: Residential Heating,* offers a practical method for estimating embodied carbon in building services equipment where Environmental Product Declarations (EPDs) are unavailable [8]. The Government of Canada's *Standard on the Disclosure of Greenhouse Gas Emissions* and the Setting of Reduction Targets establishes a framework for consistent emissions reporting, while RESNET Standard 1550 provides a precedent for integrating equipment emissions into home energy ratings [12], [13].

#### 2.4.1.2 Technical References

This study drew on a range of published technical data, LCAs, EPDs, Product Environmental Profiles (PEPs), and industry-compiled datasets to estimate equipment service life, refrigerant leakage rates, and embodied carbon impacts. Sources such as the 2019 American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) *HVAC Applications Handbook* and the ASHRAE *HVAC Service Life and Maintenance Cost Database* provide statistically derived lifespan expectations based on real-world data [14], [15]. The California Public Utilities Commission's *Roadmap*

*for Accelerating the Adoption of Low-GWP HVAC Refrigerants* offers direction on managing refrigerant emissions [16]. For end-of-life considerations and embodied emissions modelling, resources such as the ECHO Project documentation and the Carbon Leadership Forum's *End-of-Life Modeling and Data in North American Whole Building Life Cycle Assessment Tools* were consulted [17], [18].

#### 2.4.1.3 Tools

A range of tools supported emissions estimation throughout this study, particularly for refrigerants and embodied carbon. The MEP 2040 *Refrigerant Impact Calculator* and the GHG Protocol's *Refrigeration and Air-Conditioning Equipment (RAC) Tool* enable users to estimate refrigerant emissions based on equipment type, charge size, and leakage rates [19], [20]. For embodied carbon, One Click LCA is one of several platforms for modelling emissions across a range of building components, including limited modules for mechanical equipment [21]. While tool coverage for residential equipment remains incomplete, these resources provide a foundation for emissions modelling and management.

### 2.4.2 Manufacturer and Product Documentation and Databases

Publicly available product documentation and manufacturer resources were used to assess emissions, service life, and end-of-life practices for the equipment in scope. Sources include third-party databases and manufacturer-generated materials, with a focus on transparency, consistency, and alignment with circularity principles. Together, these resources inform comparative analysis and identify gaps in data availability across equipment categories. Many product resources and documentation sources were reviewed during this research; any that were consulted but not directly cited in the report are listed in Appendix B.

#### 2.4.2.1 Product Documentation and Databases

Environmental declarations were sourced from publicly accessible databases to evaluate embodied carbon, refrigerant type, material composition, expected service life, and other relevant life-cycle indicators for the equipment in scope. Key resources included the EPD International Library and its associated PCR (Product Category Rules) Library, which offer standardized reporting formats across product categories, and ÖKOBAUDAT, the German national database that is widely used in European building assessments [22], [23], [24]. European sources were frequently consulted; they served to complement North American data gaps. These sources provided consistent and comparable data, supporting emissions modelling and service life analysis.

#### 2.4.2.2 Manufacturer Warranties and Documentation

Manufacturer-provided resources, including user manuals, technical documentation, maintenance guides, and warranty documentation, sometimes reference product lifespan expectations, either explicitly or indirectly through warranty terms [25], [26], [27], [28]. Many of these documents were reviewed to determine whether manufacturers disclose intended service life, repairability considerations, or end-of-life management practices. A full list is available in Appendix B.

Corporate sustainability reports were also examined to assess whether manufacturers disclose commitments to circularity, durability, or extended producer responsibility [29], [30], [31], [32]. These reports provide insight into how manufacturers define product longevity within their sustainability strategies.

### 2.4.3 Industry Expertise

In addition to document-based research, interviews with interested parties from industry provided qualitative insights into emissions reporting practices, product durability considerations, and regulatory challenges and opportunities. To capture a range of perspectives, interviewees were grouped into four categories based on their expertise and role in the equipment value chain, with each offering distinct insights relevant to the development of emissions-focused standards.

**Manufacturers –** Gaining perspectives on emissions data availability, supply chain challenges, and material selection.

**Policy and Standards Experts –** Understanding how embodied carbon can be integrated into standards and regulations.

**LCA Practitioners –** Gathering insights on methodological challenges and data gaps in residential equipment assessments.

**Homebuilders and Contractors –** Understanding the implications of proposed standard development on participants throughout the value chain

These interviews complemented quantitative research by providing real-world considerations that might not have been fully captured in standards documentation. The findings from these discussions helped inform the report by identifying common challenges and opportunities for standard development. Interview questions are listed in Appendix C.

### 2.4.4 External Consumer Resources

Consumer resources, such as repairability research and advocacy studies, provide insight into the serviceability and durability of residential equipment. Consumer Reports offer consumer-generated data on product reliability, failure rates, and common repair needs, helping to guide user expectations regarding product longevity under typical use conditions [33]. The Consumer Technology Association conducts industry studies on consumer attitudes toward product lifespans, repairability, and end-of-life management, shedding light on market trends and consumer demand for durable products [34]. At an international level, the Organisation for Economic Co-operation and Development (OECD) supports circular economy strategies and extended producer responsibility through research and policy guidance [35]. Many resources were reviewed for this research; those consulted but not directly cited are listed in Appendix B.

## 2.5 Data Analysis

This analysis focused on three core areas: quantifying equipment emissions to determine their significance in overall building emissions, evaluating category-level variations to identify the most impactful products, and assessing the extent to which current standards address these impacts—or leave gaps (see Figure 4).

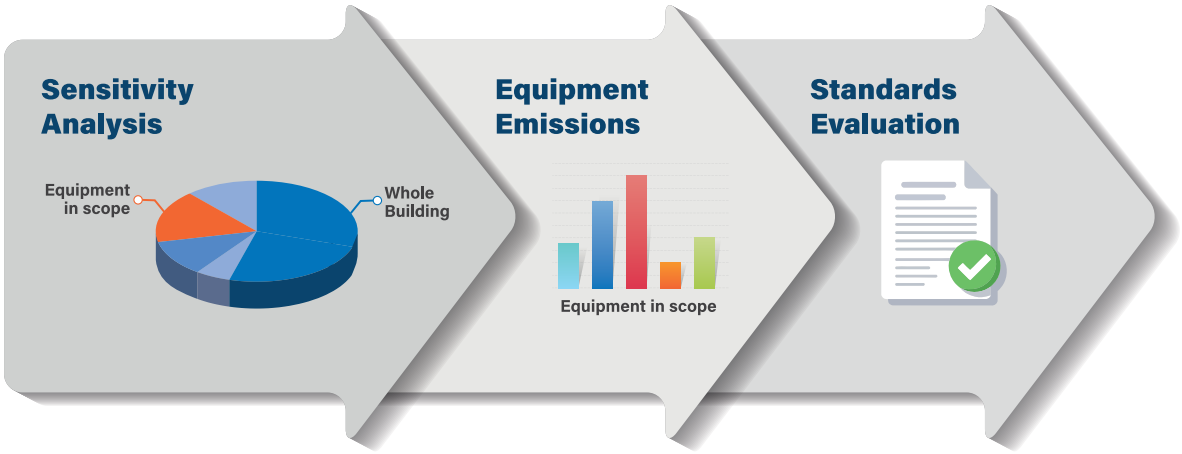
The first step was a sensitivity analysis to determine whether residential equipment emissions are substantial enough to justify their inclusion in standards and related emissions documentation. By comparing equipment emissions to the total emissions of a home, and drawing on data from LCAs, EPDs, and research sources like TM65.1, this analysis quantified how much residential equipment contributes to embodied carbon at the whole-building level.

Next, the analysis evaluated emissions at the equipment category level to identify where impacts are highest. This includes embodied carbon emissions from product manufacturing (A1 to A3 life-cycle stages, explained further in Section 3.2), as well as refrigerant-related emissions from leakage during installation (A5), operation (B1), and decommissioning and disposal (C1/C4), where data is available. Lifespan was also considered to understand how often equipment is replaced, and how that drives cumulative emissions, where data was available. The analysis identified the strongest emission drivers and validates which equipment types should be prioritized in future research and standards development.

The final stage of analysis focused on existing standards to assess whether these impacts are already being regulated, and where opportunities exist to establish standards where there are gaps. The review

**Figure 4: Framework for Evaluating Residential Equipment Impacts**

*Three-part analysis: sensitivity testing, equipment emissions profiling, and standards evaluation to identify gaps and opportunities in regulating residential equipment impacts.*




examines Canadian and international standards to determine where embodied carbon, refrigerant emissions, and equipment lifespan considerations are addressed. This comparison helps identify areas where current standards could be expanded or where new standards should be developed to address missing considerations.

# 3 Results and Discussion

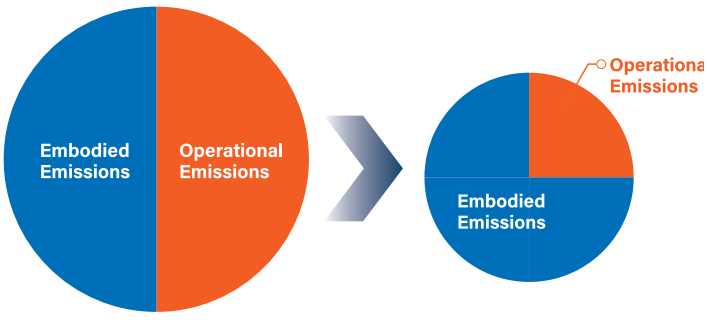
## 3.1 The Growing Significance of Embodied Carbon

Reducing the environmental impact of the built environment is increasingly urgent. The 2022 Global Status Report for Buildings and Construction by the United Nations Environmental Programme states that the building sector is responsible for over 37% of global GHG emissions [36]. These emissions arise from all building components—materials, systems, and equipment—across their life cycles. Residential equipment, which supports essential household functions, plays a substantial role in these emissions [8], [37].

Historically, decarbonization efforts have focused on operational emissions [38]. Gains in energy efficiency, electrification, and clean energy have shifted attention toward embodied carbon, the emissions "locked in" through manufacturing, transport, and installation. As operational emissions decline, embodied carbon accounts for a growing share of total life-cycle emissions [39], [40] (see Figure 5).

**Figure 5: Changing Balance of Life Cycle Emissions**

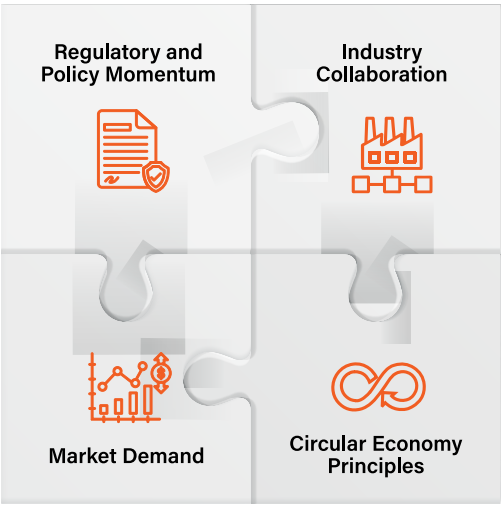
*As operational emissions decline, embodied carbon makes up an increasing share of total life cycle emissions – note that embodied emissions are the same total value in both, but making up a larger proportion of the pie in the graph on the right.*



Residential equipment presents unique challenges: short service life, frequent replacement, and reliance on high-emission components like metals and refrigerants. Although individual units may seem to have a low impact, their cumulative emissions over time can surpass those of longer-lasting structural building elements [41], [42], [43], [44]. Four key forces are driving attention to these emissions: regulatory and policy momentum, industry collaboration, shifting market demand, and the adoption of circular economy principles (see Figure 6).

**Figure 6: Drivers of Embodied Carbon Reduction**

*The four primary drivers for embodied carbon emission reductions in buildings.*




### 3.1.1 Drivers of Decarbonization: Regulatory and Policy Momentum

Policies are evolving beyond operational energy and materials to address embodied emissions in systems and equipment. The *Canadian Net-Zero Emissions Accountability Act* commits Canada to net-zero by 2050, with a 40% to 45% reduction by 2030 [10], [45], [46]. This creates an opportunity to extend emissions standards to residential equipment.

The *Canada Green Buildings Strategy* supports life-cycle carbon accounting through performance-based standards and low-carbon product design [9]. As technologies such as heat pumps become widespread, both operational and embodied impacts must be addressed to avoid unintended emissions [47]. Smaller, more efficient equipment is enabled by low-load buildings, helping to reduce embodied emissions. Achieving low-carbon buildings requires attention to both forms of emissions, as shown in Figure 7.

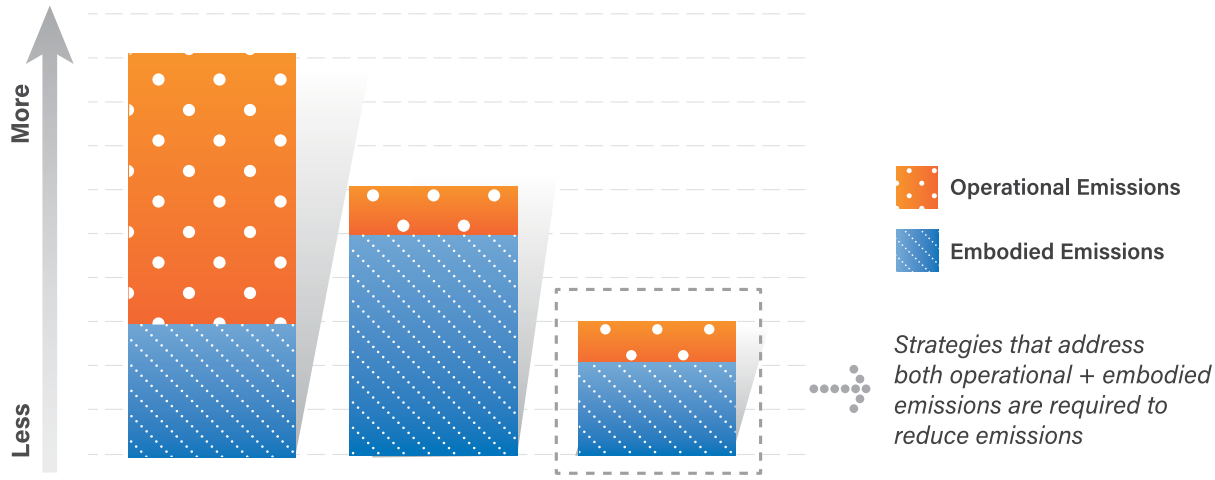
Canada's refrigerant regulations, aligned with the Kigali Amendment [48], [49], mandate phased reductions of high global warming potential (GWP) refrigerants in federally regulated equipment, as well as careful leakage monitoring. The federal Standard on *Embodied Carbon in Construction* [50] currently applies only to materials; however, it sets a precedent for expanding requirements to equipment. Provincial and municipal efforts in British Columbia, Quebec, and Vancouver reinforce this direction [51], [52], [53], [54]. These regulatory frameworks demonstrate growing policy alignment and establish a foundation for embodied carbon mandates that could readily extend to systems and equipment.

Internationally, U.S. policies like Buy Clean and the *Inflation Reduction Act* promote product transparency and low-carbon manufacturing [55], [56], [57]. Although some policies, such as the proposed *Hands Off Our Home Appliances Act* (H.R. 6192), reflect political volatility, the long-term trend is toward expanding emissions transparency and performance standards. Many state and municipal policies in the U.S. continue to advance independent of federal shifts [58], [59].

European policy provides additional precedents. *The European Green Deal* and the *Paris Agreement* [60] are shaping integrated embodied carbon regulations, such as France's RE2020, which mandates progressive reductions in construction emissions and requires the reporting of product-level environmental data [61], [62], [63]. These policies demonstrate how digital transparency, product labelling, and whole life-cycle accounting are becoming regulatory norms. Digital Product Passports, required under the European Union's (EU's) *Ecodesign for Sustainable Products Regulation* (ESPR) and *Circular Economy Action Plan* [64], and revisions to the EU's *Construction Products Regulation* [65], also show how embodied carbon and circularity can be embedded into product standards.

**Figure 7: Dual Strategies for Low-Carbon Buildings**

*Reductions in both operational and embodied emissions are required to achieve low-carbon buildings.*




Aligning Canadian standards with these global trends could help mitigate trade risks and position Canada for leadership in low-carbon equipment design. At the same time, regulatory and policy momentum in Canada will create stronger drivers for advancing standards development, while robust standards will reinforce and enable effective policy implementation. Together, they form a mutually reinforcing pathway toward decarbonizing residential equipment.

### 3.1.2 Drivers of Decarbonization: Industry Collaboration

Cross-sector collaboration is increasingly targeting embodied emissions. Organizations such as ASHRAE and the World Green Building Council promote policy development and research [66], [67]. In Canada, industry and advocacy play an essential role in promoting sustainability standards, advancing performance-based construction, and supporting policy innovation [68], [69]. Canada Green Building Council's (CaGBC's) Zero Carbon Building Standard integrates operational and embodied emissions into carbon accounting frameworks, while Efficiency Canada and Clean Energy Canada focus on policy advocacy and public engagement [70], [71].

Standards development further reflects this shift. RESNET 1550 incorporates MEP systems in residential whole-building modelling [13], while ASHRAE/ICC 240P provides a similar approach for commercial projects [72]. Supporting resources like Chartered Institution of Building Services Engineers' (CIBSE) TM65, *Embodied carbon in building services: A calculation methodology,* TM65.1, *Embodied carbon in building services: Residential heating,* and TM65NA, *Embodied Carbon in Building Services: A Calculation Methodology for North America* offer practical methods to estimate emissions from systems, including refrigerant-related impacts [8], [43], [73].

Collaborative initiatives like the Carbon Leadership Forum and Building Transparency's EC3 tool are helping procurement teams make carbon-informed decisions [74], [75]. The ECHO Project works to harmonize data frameworks, while PACT (Partnership for Carbon Transparency) demonstrates how transparent emissions reporting can scale across industries, including electronics [76], [77]. Alignment and coordination between these groups is essential to accelerate standards development, harmonize data, and scale emissions reduction efforts.

Collaborative initiatives extend beyond technical standards. Voluntary programs, like Living Future's Zero Carbon Certification, incorporate emissions accounting within their rating systems [78]. Industry commitments like SE2050 and MEP2040 are shaping expectations for embodied carbon reporting, as well as accurate accounting of refrigerant use in mechanical, electrical, and plumbing (MEP) systems [79], [80]. HomebuildersCAN and additional Carbon Action Networks support builders, manufacturers, and owners in low-carbon practices [81], [82]. Design leaders are also aligning with these efforts through the Architecture 2030 Challenge and AIA 2030 Commitment [83], [84].

These efforts demonstrate growing attention to embodied carbon across the building sector and show that a broad range of actors are mobilizing around its measurement and reduction. Work to address the embodied emissions of residential equipment can build on this momentum to inform future standards, tools, and regulatory approaches.

### 3.1.3 Drivers of Decarbonization: Market Demand and Consumer Awareness

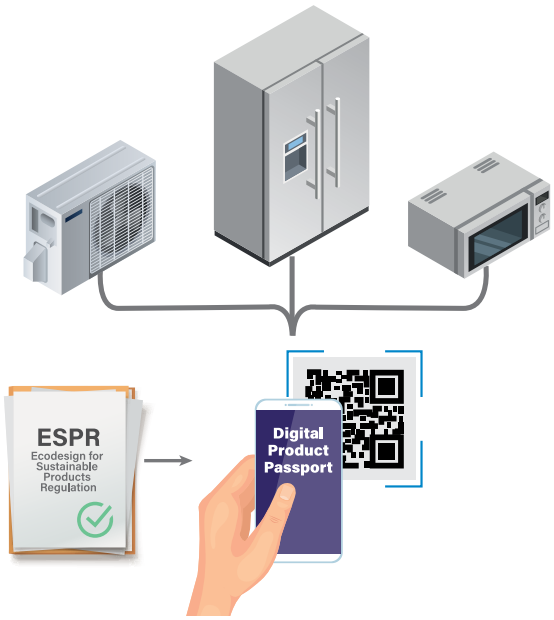
Market demand and consumer awareness are increasingly influencing emissions reduction in residential equipment. Programs like ENERGY STAR, EnerGuide, and regional efficiency rebates have established expectations for performance [85], [86], [87], [88]. Expanding these frameworks to include embodied carbon could help strengthen consumer decision making and reward low-carbon innovation. The proposed U.S. EPA Carbon Label Program provides a model for providing accessible information to promote environmentally responsible purchasing [89], [90]

Green building certifications, such as CaGBC's Zero Carbon Standard, LEED (Leadership in Energy and Environmental Design), and Living Future programs, emphasize how product-level transparency contributes to meeting whole-building performance and carbon reduction goals [70], [72], [91], [92]. Declare labels and initiatives by groups like mindfulMaterials and the Cradle to Cradle Products Innovation Institute focus more narrowly on improving material health, circularity, and sustainability within product design and manufacturing processes [93], [94], [95].

European tools, such as the EU Ecolabel and Digital Product Passports, illustrate how emissions data can be standardized and made accessible (Figure 8) [61], [96]. These tools help consumers make informed decisions and support industry accountability, and they could be adapted for use in Canadian equipment labelling and procurement systems.

**Figure 8: Digital Product Passports in Equipment Labeling**

*Digital Product Passports, created under the European Union's Ecodesign for Sustainable Products Regulation (ESPR), show how product-level data is linked to equipment through labeling systems.*




Tools like the Community Technology Assessment Platform (CTAP), developed by Natural Resources Canada to aid communities in setting local GHG reduction strategies, reflect the growing recognition of residential equipment as a meaningful contributor to building-sector emissions. While CTAP focuses on operational emissions, its inclusion of equipment-related energy use underscores the need for a more holistic treatment of these systems. Tools like this signal that residential equipment is no longer a marginal concern. Expanding these platforms to consider product-level embodied carbon would support more comprehensive, life-cycle–informed decision making at the local level [97].

Contractors are also responding to shifting expectations. Interviews conducted for this research revealed that many are already integrating embodied carbon assessments into project planning. However, contractors emphasized the need for greater standardization, consistent data, and practical guidance to meet anticipated reporting requirements. Several interviewees viewed embodied carbon policy as a cost-effective pathway to emissions reductions, particularly in contrast to increasingly stringent energy efficiency requirements. This perspective underscores the opportunity to develop clear, actionable standards for residential equipment.

Environmental, social, and governance (ESG) reporting is further accelerating data disclosure. Publicly traded companies and large home builders view emissions transparency as a business imperative [98]. During interviews conducted for this research, manufacturers noted that strong market signals and procurement policies are needed to drive consistent disclosure. Voluntary actions alone are unlikely to scale without public and consumer pressure. Integrating embodied carbon into market-facing systems could help close this gap, supporting market transformation and accelerating the adoption of low-carbon design.

### 3.1.4 Drivers of Decarbonization: Circular Economy Principles

Circular economy principles offer an actionable strategy for reducing equipment emissions by extending service life and recovering materials. This is particularly relevant for short-lived, high-impact products like residential equipment and appliances.

Circular practices—reuse, repair, refurbishment, and recycling—can reduce material demand and emissions [94], [99]. As shown in Figure 9, these strategies replace the traditional linear life cycle with a looped system of material recovery and reuse. While this report focuses on GHG emissions, circular strategies also reduce landfill burden, lower consumer costs, and support long-term resource resilience.

A core component of circularity is Value Retention Processes (VRPs), such as remanufacturing, repair, and refurbishment, which extend product lifespans and reduce material waste through manufacturer-led practices [100]. Remanufacturing alone can save up to 80% of the energy used to produce new products [101]. For example, Whirlpool reported refurbishing over 95,000 small appliances in 2024 [102], but such efforts remain rare, and public details are often limited or withdrawn. Manufacturers rarely disclose which components are retained or how products are recertified for safety, and this lack of transparency is a key barrier to assessing climate benefits. Standardized metrics for repairability, durability, and emissions performance could help clarify these practices and help them scale.

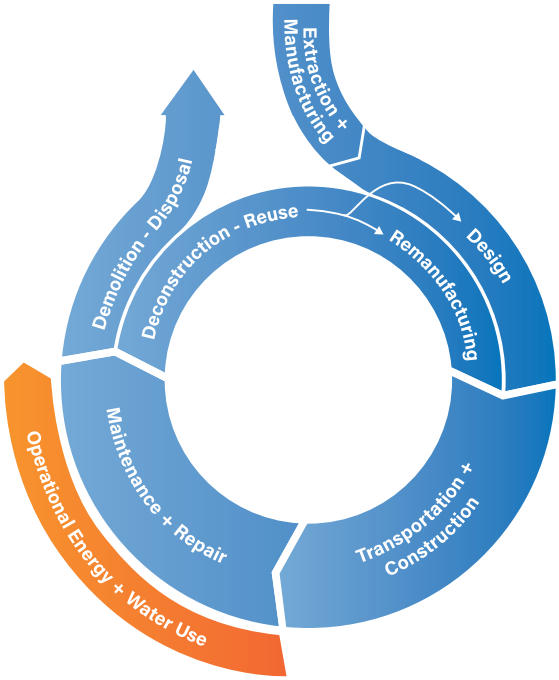
Refrigerant reclamation is another opportunity. Daikin's recovery programs aim to reduce both embodied and operational emissions, although third-party verification could improve credibility [103], [104]. Broad material reuse also plays a role. Steel recycling prevented the need for approximately 680 million tonnes of virgin production in 2021 alone, offering a model for what circular systems can achieve when fully developed [105]. Similar potential exists for electronics and residential equipment.

International policy is beginning to embed circularity into regulation. The EU *Circular Economy Action Plan* prioritizes durability and waste prevention [64], [106]. The ESPR and Level(s) framework integrate circular design and performance standards, while the Waste Electrical and Electronic Equipment (WEEE) Directive sets explicit rules for producer responsibility and material recovery for electronic and electric equipment [107], [108]. These policies target not only carbon emissions but also broader ecological impacts such as toxicity and pollution.

Canada is beginning to explore comparable approaches. Recent research into repairability, disassembly, and product life extension has identified key barriers, including limited access to spare parts and restrictive design practices [109], [110], [111]. Leveraging these domestic insights could support the integration of circular economy principles into residential equipment policy, highlighting the need for standardized VRP metrics and product longevity strategies to reduce emissions in the sector.

**Figure 9: Rethinking the Product Life Cycle - From Linear to Circular Emissions Pathways**

*Circular economy strategies reduce emissions by rethinking the product life cycle. This diagram illustrates a looped system of reuse, repair, and remanufacturing, replacing the traditional linear path of extraction, use, and disposal shown in Figure 1.*




The residential equipment sector is well-positioned to lead on circular product design. Adopting lessons from the EU's ESPR and WEEE Directive could help reduce emissions, foster innovation, and align with global climate goals. Standards and policies will be essential to turning pilot projects into scalable solutions.

### 3.1.5 The Imperative for Action: The Impact of Residential Equipment

While operational efficiency has improved across HVAC systems, appliances, and electronics, embodied carbon has received far less attention [112], [113]. As Canada moves toward a net-zero electricity grid by 2035 [114], the relative impact of embodied emissions will continue to grow.

Early emissions reductions are essential (see The Time Value of Carbon insert on Page 18). While operational emissions still dominate for the whole life-cycle emissions of many products, embodied emissions are becoming increasingly significant, especially for frequently replaced systems.

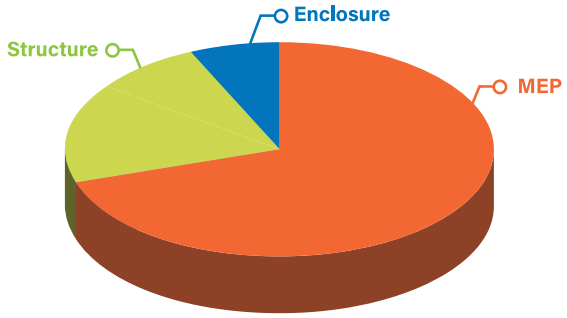
MEP systems exemplify this trend. TM65.1 and the LETI Primer report that MEP components make up 15% to 27% of embodied carbon in new construction and up to 49% in retrofits [8], [115]. *The Beginner's Guide to MEP Embodied Carbon* from MEP2040 found that MEP systems contributed 27% of cradle-to-gate emissions in a commercial project. This increased to 53% when refrigerant leakage, repairs, and replacements were included, and to 73% when operational energy and water were added (see Figure 10). While based on a commercial case, these results reinforce the significant role of systems across contexts.

Other product-specific studies show similar findings. Manufacturing accounts for up to 26% of a washing machine's life-cycle emissions [41], and approximately 30% for televisions [116]. In both instances, these figures will grow as grid emissions decline [117]. In high-performance homes, HVAC systems can represent up to 56% of total embodied GHGs over 60 years [118]. Multiple replacements, refrigerant losses, and material intensity amplify these impacts [42], [44].

Reducing these emissions requires durable design, low-GWP refrigerants, and material efficiency. However, strategies must be implemented thoughtfully to avoid trade-offs related to toxicity, recyclability, or service life. Standards must reflect the full climate burden of residential equipment. With tools, data, and policy mechanisms in place, the sector has a clear path forward.

**Figure 10: Whole-Building Emissions by Equipment and Other Systems**

*MEP systems can represent a significant share of whole-building life cycle emissions, as shown in this graphic adapted from the Beginner's Guide to MEP Embodied Carbon. Although this example reflects commercial buildings, the impact of residential equipment is also considerable, yet less studied, highlighting a key data gap.*



## The Time Value of Carbon

The time value of carbon accounts not just for the amount of emissions, but also when they occur. Embodied carbon emissions, especially those from early life-cycle stages (A1 to A5), are "locked in" before a building becomes operational. These early emissions have a greater impact on near- and mid-term climate targets and remain in the atmosphere longer, making their cumulative effect more severe. Treating all emissions as equal across the life cycle overlooks this urgency and can lead to missed opportunities for meaningful reductions [119].

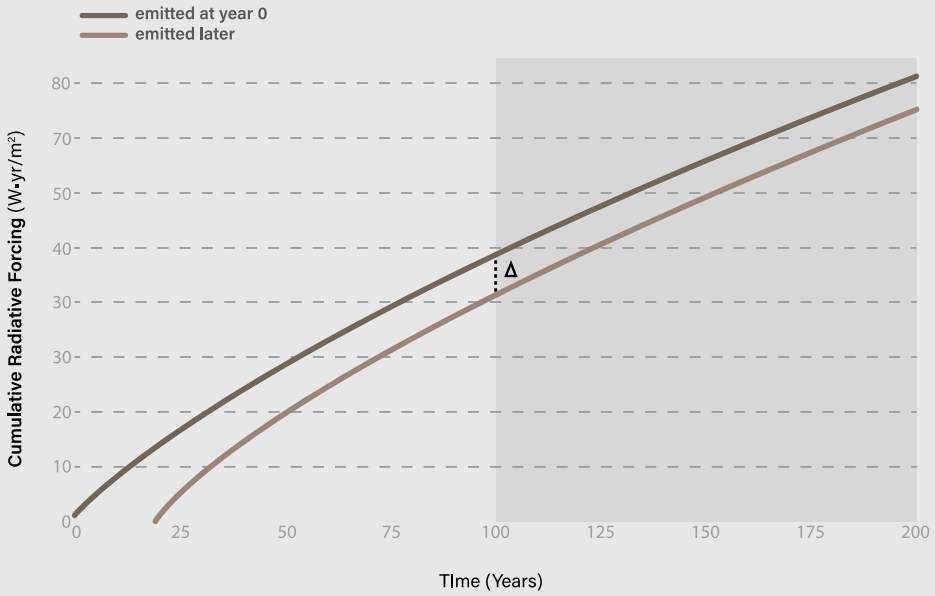
Dynamic life-cycle assessment (DLCA) provides a framework for capturing this effect. Unlike conventional LCA, which treats all emissions the same regardless of timing, DLCA emphasizes the importance of reducing emissions that occur early in a product's life, as evidenced by the difference in outcomes after 100 years shown in Figure 11. Several approaches are under development or debate internationally, including varying the time horizon for global warming potential (GWPx), modelling carbon decay and sequestration over time, and calculating carbon payback periods based on operational energy savings [120], [121].

These approaches are beginning to influence international standards. The European Commission's Level(s) framework highlights the importance of timing in LCA reporting, and the Intergovernmental Panel on Climate Change (IPCC) has encouraged the use of shorter GWP time frames to reflect the urgency of near-term climate targets [62], [122]. National governments have also begun considering the time value of carbon, with France mandating the application of weighting factors based on the year of emission, discounting future emissions compared to those released today [63]. As DLCA tools and methodologies mature, they offer a path for integrating time sensitivity into building-related standards.

For residential equipment, where early-stage embodied emissions can be high and service lives short, timing matters. Products that require frequent replacement or contain high-GWP materials like refrigerants contribute disproportionately to near-term climate impacts. Prioritizing emissions reductions during the early stages—through better design, material selection, and product durability—can significantly improve climate outcomes and align with Canada's net-zero goals.

**Figure 11: Cumulative Radiative Forcing of $CO_2$ Emitted at Different Times**

*Cumulative radiative forcing resulting from carbon dioxide emitted at different times, highlighting the increased cumulative effect of early life cycle emissions. This is one of the ways that Dynamic LCA methods differentiate the climate impact of emissions released today versus those delayed into the future.*



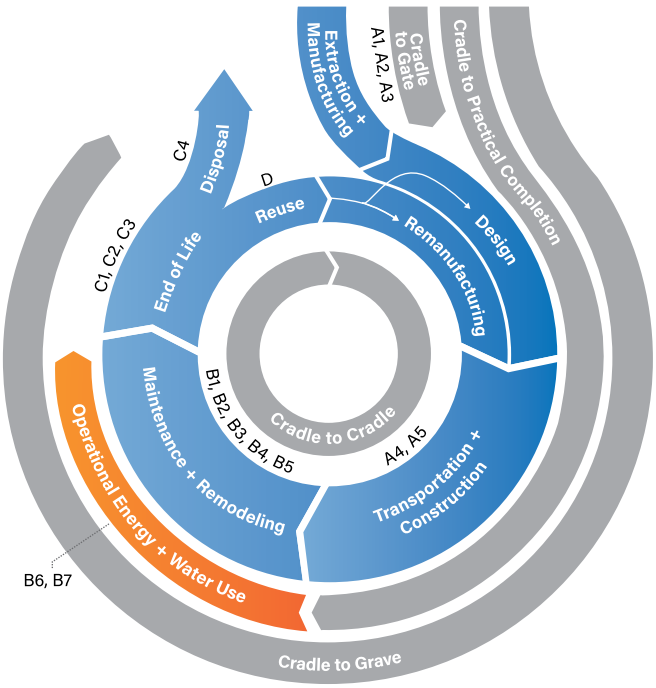
## 3.2 Reducing the Impact of Residential Equipment

### 3.2.1 How Embodied Carbon is Measured

Effectively reducing emissions in the built environment requires a clear understanding of how they are measured. Life cycle analysis provides a structured methodology for evaluating the environmental impacts of products, systems, or buildings across their entire lifespan [123]. It distinguishes embodied emissions (from material production, installation, maintenance, and end-of-life) from operational emissions (energy and water use), using clearly defined stages as illustrated in Figure 12.

**Figure 12: LCA Reporting Scopes and Stages**

*Life cycle stages for whole-building LCA, distinguishing embodied emissions (A1–A5, B1–B5, C1–C4, in blue) from operational emissions (B6, B7, in orange). Common reporting scopes (illustrated with grey arrows) include cradle-to-gate (A1–A3), cradle-to-grave (A1–C4), and cradle-to-cradle when reuse or recovery benefits (D) are included.*




**Product Stages** (**A1** to **A3**): These stages cover raw material extraction (A1), transportation (A2), and manufacturing (A3). These stages contribute to embodied emissions, as they encompass the materials and processes involved in creating a product. A1 to A3 typically represent the most significant sources of embodied emissions, as they encompass the energy- and resource-intensive processes of material extraction, refinement, and production. These stages are often referred to as *cradle-to-gate* or *material emissions.*

**Construction Stages** (**A4** to **A5**): These stages cover product transportation to site (A4) and construction or installation of the product (A5). Combined with the product stage, collectively A1 to A5 is often referred to as *upfront emissions* or *pre-operational/pre-use emissions.*

**Use Stages** (**B1** to **B7**): These stages include impacts from use (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5), all of which contribute to embodied emissions, and are referred to as *use stage*. These stages also account for operational energy use (B6) and operational water use (B7), which are categorized as *operational emissions.*

**End-of-Life Stages** (**C1** to **C4**): These stages encompass deconstruction (C1), transport (C2), waste processing (C3), and disposal (C4). These stages contribute to embodied emissions as they relate to waste management and material recovery processes. When all stages from A1 to C4 are combined (exclusive of B6 and B7), they are collectively referred to as *cradle-to-grave* or *embodied carbon emissions*.

**Beyond the Life Cycle (D)**: This stage falls outside the typical LCA scope and represents the benefits of circular economy practices. It accounts for the impacts of repurposed waste into new resources, reducing the need for virgin materials, and slowing the flow of materials toward disposal and landfill. When the D stage is incorporated into an LCA, it could be referred to as *cradle-to-cradle*.

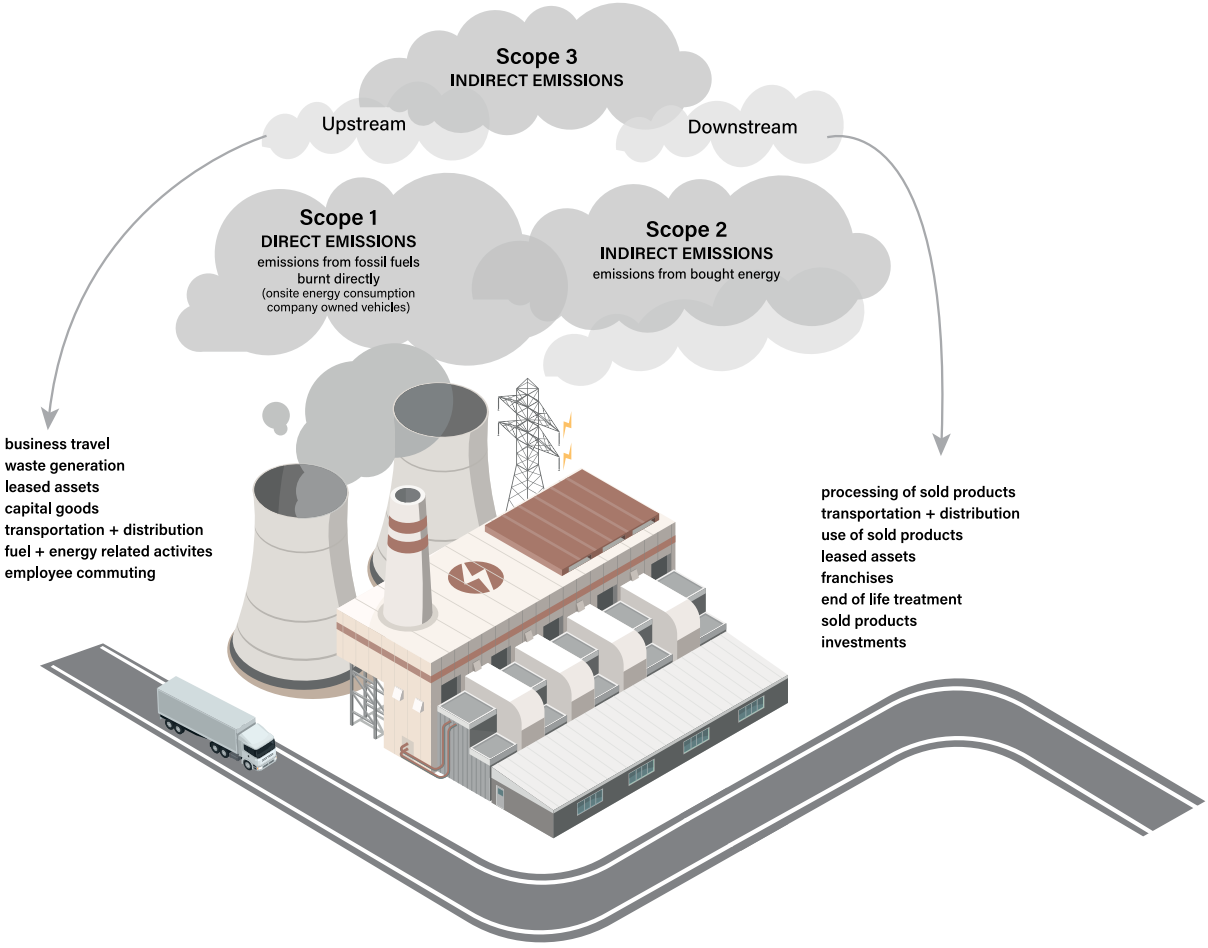
While operational emissions have historically been the focus of efficiency measures, this report expands that focus by exploring tools and methodologies for assessing embodied carbon. LCA provides one approach, but regulatory and market frameworks categorize emissions into scope 1, 2, and 3—distinctions that are important for understanding how emissions responsibility is assigned across the supply chain (see Figure 13) [124], [125]. For clarity, the scope categories are defined below:

- **Scope 1:** Direct emissions from activities under an organization's control, such as on-site manufacturing, fuel combustion in company-owned equipment, or emissions from industrial processes.
- **Scope 2:** Indirect emissions from the generation of purchased energy, including electricity, steam, heating, or cooling used by the organization.
- **Scope 3:** Indirect emissions occurring outside an organization's direct operations, including upstream emissions from raw material extraction, production, and transportation, as well as downstream emissions from product use, maintenance, and end-of-life disposal.

These categories provide a framework for understanding emissions responsibility across different industries. In the building sector, scope 3 emissions, particularly those from materials and equipment, are becoming a focal

**Figure 13: Categorizing Building Sector Emissions**

*Greenhouse gas emissions are categorized as Scope 1 (direct emissions from owned or controlled sources), Scope 2 (indirect emissions from purchased energy), and Scope 3 (all other indirect emissions across the supply chain). This illustration highlights how upstream and downstream activities—including material production, transportation, product use, and end-of-life treatment—contribute to Scope 3 emissions for the building sector.*



point of regulatory and market pressures. In many cases, they represent the largest share of a building's total emissions profile, often exceeding operational emissions over the full life cycle [125]. While scope 1 and 2 emissions have long been the target of energy efficiency measures, scope 3 emissions, related to materials, products, and equipment, are now under increasing scrutiny. Given that practitioners of building design and construction influence material selection, procurement, and system specifications, they play a critical role in shaping a building's scope 3 emissions. As embodied carbon regulations gain momentum, interested and affected parties will need to prioritize materials and equipment with lower life-cycle emissions to meet emerging sustainability targets.

A building's scope 3 emissions largely stem from the upstream and downstream activities of its supply chain, including the extraction, manufacturing and end-of-life processing of materials and equipment. This means that the manufacturers' scope 1 and 2 emissions—the direct emissions from production facilities and energy use—become the scope 3 emissions of the buildings they supply. As buildings face rising expectations to account for and reduce their total life-cycle emissions, manufacturers must adapt by lowering both the operational and embodied carbon impacts of their products to remain competitive in a decarbonizing market. This shift is being accelerated by emerging policies that are driving new requirements for embodied carbon transparency and reductions in the building sector (see 3.1.1 Drivers of Decarbonization: Regulatory and Policy Momentum). Procurement standards and voluntary reporting frameworks are accelerating this shift, reinforcing the need for manufacturers to measure and disclose life-cycle emissions.

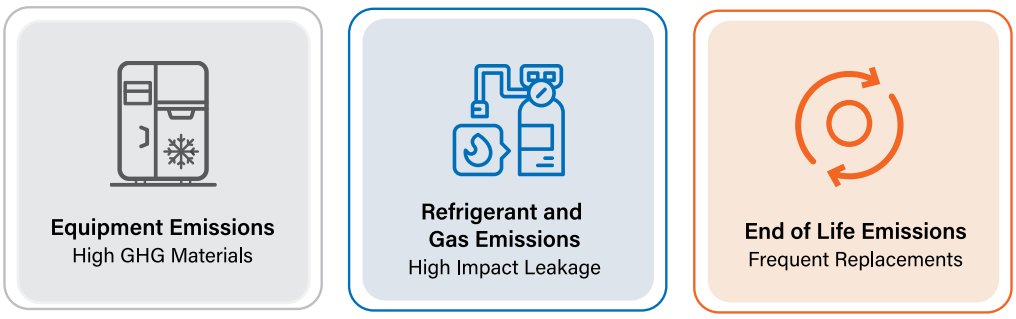
These concepts provide the foundation for evaluating embodied carbon in residential equipment. Unlike simpler and long-lived materials, residential equipment has distinct scope 3 challenges, including frequent replacement, refrigerant emissions, and complex multi-component manufacturing. The next section explores these factors in greater depth, examining the methodologies and strategies needed to reduce their impact.

### 3.2.2 Specialized Considerations for Embodied Carbon Measurement of Residential Equipment

Residential equipment contributes to GHG emissions in ways that can be bundled into three primary categories, as shown in Figure 14: GHG emissions from producing the equipment; the emissions associated with refrigerant and gas leakage used in the equipment; and the short service lives and replacement cycles for equipment. There are unique embodied carbon measurement challenges associated with each of these categories.

**Figure 14: Primary Categories of Emissions in Residential Equipment**

*There are three primary categories of greenhouse gas emissions associated with residential equipment: 1) the emissions associated with the production of the equipment, including high-emission materials such as metals and circuitry; 2) the emissions associated with the leakage of refrigerants and gas built into or fueling the equipment, and; 3) emissions released repeatedly over the lifetime of a building due to the short lifespans and frequent replacement cycles of the equipment.*



Quantifying the equipment in residences in a consistent and standardized manner is different from doing so in larger, non-residential buildings, where more complete mechanical designs and bills of materials are typically produced, aiding in emission assessments. RESNET Standard 1550 provides a precedent as to how to achieve equipment emission information in residential applications [13].

Unlike structural components, which are expected to last for the life of the building, residential equipment undergoes frequent replacement due to shorter lifespans, consumer choice, and rapidly evolving technology [126]. Each replacement cycle contributes additional embodied carbon emissions from manufacturing (A1 to A3), transportation (A4), and disposal (C1 to C4), compounding the total life-cycle impact over a building's lifespan [8], [37].

Refrigerant leakage occurs at multiple stages, including manufacturing, installation, use, and disposal, contributing to significant emissions. Complex systems, such as HVAC and refrigeration units, often require multiple recharges over their lifespan due to leaks or maintenance needs, further increasing their total carbon impact.

Electronic components, such as circuit boards and LED screens, are highly material-intensive, contributing significantly to material carbon emissions (A1 to A3) [42]. Their manufacturing requires energy-intensive processes, further amplifying embodied emissions [127]. Additionally, the complexity of these components increases the likelihood of malfunction, often leading to replacement of the full unit rather than part repairs. This highlights the need for modular designs that facilitate component replacement, extend product life, reduce waste, and enable resource recovery. Addressing these challenges requires targeted strategies and standards that account for the full life-cycle impact of residential equipment.

## 3.3 Sensitivity Analysis

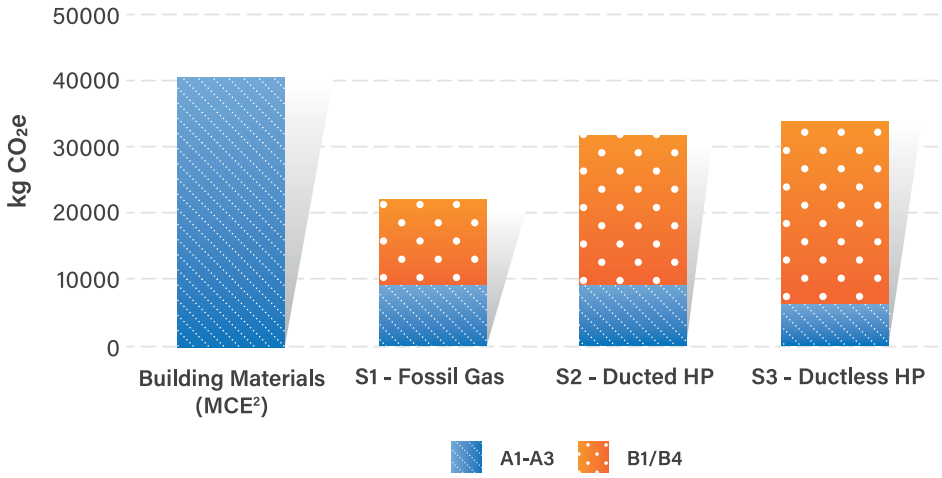
Data availability for this type of analysis remains limited, particularly in residential contexts, where fewer LCAs and EPDs exist for smaller-scale equipment. Additionally, many studies benchmark general building materials using A1 to A3 emissions only, while emissions studies for equipment often extend across the full life cycle. This inconsistency makes direct comparison difficult. Harmonizing scope boundaries, so that A1 to C4 emissions for materials and equipment can be evaluated on equal footing, will be critical for future standards and assessments. While precise and repeated study of the relative impact of residential equipment emissions on whole-building emissions is not currently available, there is sufficient data in both residential wbLCA benchmarking and residential emissions rates to confirm the importance of managing embodied emissions from this equipment.

Builders for Climate Action led the development of the NRCan Material Carbon Emissions Estimator ($MCE^2$), a tool used to model the embodied carbon of building materials. As $MCE^2$ does not account for MEP equipment, two related research projects—the NRCan Material Carbon Emissions Estimator ($MCE^2$) MEP Data and Resource Assessment and the MEP Dataset Development—were undertaken to expand data availability and improve understanding of MEP-related emissions. These projects modelled MEP systems for a typical Canadian home alongside an $MCE^2$ model, and provide a key reference point for this study.

MEP equipment for this study included heating, cooling, ventilation, hot water service, typical electrical system components, plumbing fixtures, pumps and fans, piping, wiring, ducting, and fugitive refrigerant emissions. In this analysis, shown in Figure 15, A1 to A3 emissions from MEP systems alone (excluding refrigerants or replacements) ranged from 6,400 to 8,800 kg $CO_2e$, representing approximately 14% to 18% of the total building A1 to A3 emissions. When R-32 refrigerant leakage emissions and equipment replacements were factored into B-stage emissions over a 60-year period, emissions rose to 22,000 to 33,000 kg $CO_2e$. In relation to total building emissions, the embodied material and refrigerant emissions for the MEP systems represent 35% to 45% of total life-cycle emissions. This proves the high sensitivity of equipment emissions as a portion of total building emissions. This analysis is not a comprehensive study of the life-cycle impacts of MEP equipment,

**Figure 15: Building GWP Emissions For Different Heating Systems**

*Total MEP GHG emissions in kg $CO_2e$ for three scenarios with R32 refrigerant compared to the MCE² values for the building structural, enclosure, partition, and primary finish material A1-A3 emissions. Note that emissions from leakage of fossil gas outside the building is not included and would alter the results of the analysis if included.*




as no B-stage emissions for non-MEP materials are considered here, although the majority of residential building embodied carbon emissions are from the A1 to A3 stage.

Further, the equipment in scope in the NRCan study does not match that of this research, in that plumbing and distribution materials are outside this research scope. However, this gives a clear indication of the importance of MEP-related equipment and refrigerant emissions in residential construction, particularly as there is significant overlap in scope with heating, cooling, and hot water equipment. It also underscores a critical insight: while A1 to A3 emissions are commonly benchmarked, B- and C-stage emissions—especially refrigerant leakage and equipment replacement—may become the dominant contributors to total life-cycle emissions in residential equipment.

Findings from the Gergely et al. study reinforce this conclusion. Their analysis of residential HVAC systems across a range of buildings found that equipment accounted for 10% to 35% of total building life-cycle emissions, largely due to embodied and refrigerant emissions [118]. The study also emphasized how repeated replacement of short-lived HVAC components can rival or exceed the embodied impact of structural materials over time.

Additional findings from TM65.1 further reinforce the significance of equipment emissions in residential buildings. The study evaluates the embodied carbon emissions of 13 different heating and hot water system options, using the TM65 methodology across a range of building scales, from a single-unit three-bedroom home to a 2,000-unit development. For a typical new home with a total embodied carbon footprint of 800 kg $CO_2e$, the embodied carbon of the heating system alone, excluding refrigerant emissions, can represent up to 25% of the total emissions load. The study found average embodied carbon emissions of 83 kg $CO_2e/m^2$ without refrigerant leakage, which increased to 164 kg $CO_2e/m^2$ when refrigerant leakage was included. When these figures are added to the 184 kg $CO_2e/m^2$ average building material benchmark from research conducted by Magwood et al. [128], the combined total represents 31% to 47% of total emissions. While the comparison combines whole life-cycle emissions of equipment with

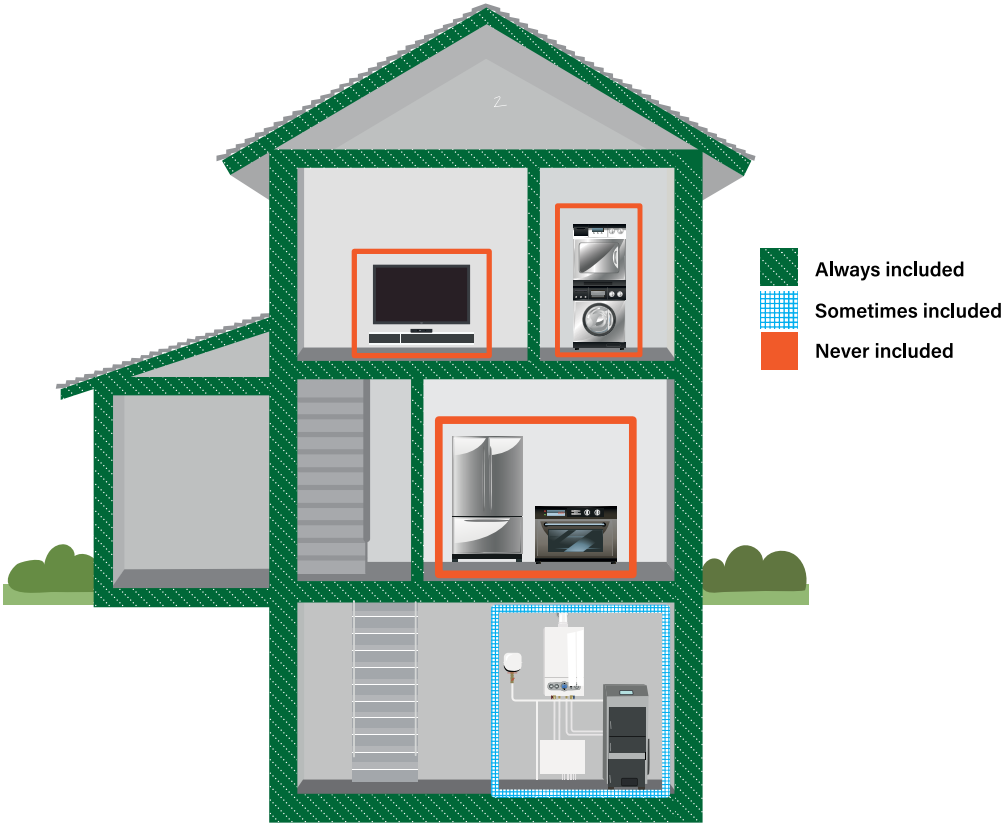
cradle-to-gate emissions of materials, the alignment across methods supports the conclusion that residential mechanical equipment plays a substantial and under-addressed role in total building emissions.

Together, these results point to a growing share of total emissions being tied to residential equipment, especially as Canada decarbonizes its grid and moves toward heat pumps and other refrigerant-based technologies. As operational emissions decline, the proportion of equipment-related emissions, particularly from materials, refrigerants, and replacements, will grow in relative significance.

The above analyses do not include all the equipment in the scope of this research. Appliances (e.g., refrigerators, dishwashers, washing machines) and smaller electronics (e.g., monitors, set top boxes, battery chargers) remain unrepresented in whole building LCA accounting. Figure 16 visually expresses which elements in a residential home are always, sometimes, and never included in wbLCA scope. Data limitations persist (see Section 4.1), and many of the products in this study's scope fall outside typical wbLCA boundaries. However, early LCA data (cited above) suggests that their cumulative emissions, especially over multiple replacement cycles, are significant.

**Figure 16: Whole Building LCA Scope Inclusions and Exclusions**

*Residential equipment is often excluded from whole-building life cycle assessment (wbLCA) scope. This illustration shows typical household systems and their varying inclusion in wbLCA: some are always included (e.g., structure), some are sometimes included (e.g., HVAC systems), and others, like appliances and electronics, are almost never included. The equipment examined in this research crosses these boundaries.*



## 3.4 Equipment Emission Outcomes

### 3.4.1 Equipment Embodied Carbon Emissions – Key Findings

Equipment emissions encompass the GHG emissions generated across the full life cycle of residential equipment, from material extraction to manufacturing, use, maintenance, and end-of-life. Reducing these emissions is essential for minimizing the environmental footprint of buildings, particularly as operational emissions decline and embodied impacts become more prominent.

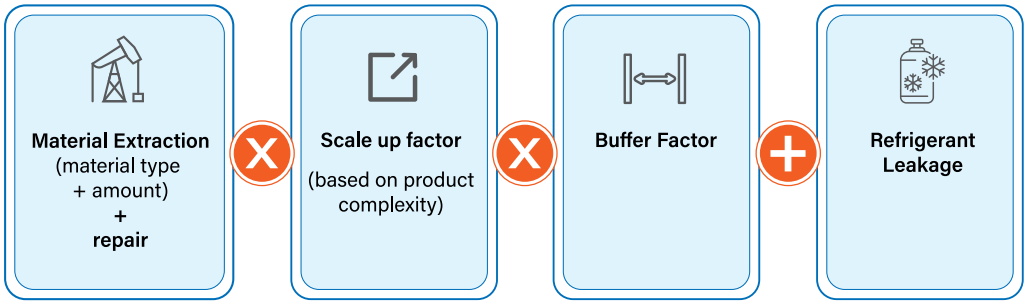
The embodied carbon of residential equipment is shaped by several interrelated factors, including material selection, manufacturing processes, product complexity, and energy inputs. Emissions intensities vary widely by material type, particularly for metals, plastics, and electronic components, and can be reduced through the use of recycled content, streamlined manufacturing, and cleaner energy sources. LCAs of portable air conditioners, for example, show that embodied emissions vary significantly based on refrigerants, metals, and electronic components [129], while equipment produced in facilities powered by renewable energy releases considerably fewer emissions than those manufactured with fossil-based energy sources [41], [117].

Among these factors, mass and material composition are especially important. Products with greater mass and more emission-intensive components, such as steel, aluminum, copper, circuit boards, and high-GWP insulative plastics, generally exhibit higher emissions. The use of composite materials that are difficult to disassemble or recycle at end-of-life can further increase emissions burdens. TM65NA reinforces these relationships by applying a scaling factor based on equipment mass and complexity, acknowledging that heavier, more intricate systems tend to require longer supply chains and more refined manufacturing processes [43]. A simplified version of TM65NA methodology is shown in Figure 17, illustrating the factors that inform emissions calculations. This is consistent with findings from now-withdrawn CSA/AHAM/UL sustainability standards, which linked larger appliance size to higher life-cycle emissions in categories such as refrigerators, cooking appliances, and floor care devices [130], [131], [132], [133].

EPDs and PEPs are becoming essential tools for quantifying and comparing embodied carbon impacts. Programs such as LEED, BREEAM, and the Toronto Green Standard incorporate EPDs into embodied carbon assessments, while Canadian federal procurement policies now require EPDs for federally funded construction projects [14]. Vancouver's

**Figure 17: Simplified TM65NA Methodology**

*This figure presents a simplified version of the TM65NA methodology, outlining how material extraction, scale-up, buffer factors, and refrigerant leakage are used to generate equipment emission impact*



embodied carbon reporting requirements build on this momentum at the municipal level. In the private sector, firms like EllisDon have integrated EPDs into their procurement processes to support low-carbon product selection. However, residential equipment remains under-represented in environmental reporting frameworks, and existing data sources are often fragmented and inconsistent, particularly for smaller appliances and electronics. A full list of all PCRs, LCAs, and EPDs reviewed for equipment in scope can be found in Appendix D.

While A1 to A3 (cradle-to-gate) emissions typically dominate a product's life-cycle emission profile, life-cycle emissions extend well beyond manufacturing, particularly for refrigerant-based equipment. Frequent equipment replacements due to short service lives contribute significantly to cumulative embodied impacts. Studies show that MEP systems—including HVAC equipment and appliances—can account for 15% to 27% of initial building embodied carbon emissions [7], [115], [118], [134]. While HVAC equipment typically has higher embodied carbon per unit (500 to 800 kg $CO_2e$) [13], studies show that dishwashers and washing machines still carry notable embodied emissions (~130 to 230 kg $CO_2e$), especially given their shorter lifespans (8 to 12 years vs. 15 to 20 years for HVAC) [41], [135]. Over time, the cumulative impact of frequently replaced appliances can be significant, particularly due to their metal and electronics content. Fewer studies exist on these products, but TM65.1 and select EPDs help fill the gap. Over a building's lifespan, replacements, maintenance, and upgrades substantially increase total emissions, reinforcing the importance of including equipment in wbLCA methodologies.

Available EPDs and LCAs reveal clear patterns across appliances and electronics. An EPD for a residential refrigerator reported 401 kg $CO_2e$ for A1 to A3 emissions and 574 kg $CO_2e$ in total embodied emissions. Over a seven-year lifespan, operational emissions reached 1,190 kg $CO_2e$, placing embodied carbon at approximately 33% of total life-cycle emissions [136]. Similarly, EPDs for monitors showed A1 to A3 emissions averaging 276 kg $CO_2e$, with operational emissions over a four-year lifespan (the lifespan reported by the EPDs) adding 154 kg $CO_2e$—resulting in embodied carbon representing 64% of total life-cycle emissions. Short lifespans and low operational demands amplify the embodied share of total emissions, an effect also noted in LCA studies of televisions, which similarly highlight production as the primary emissions driver [116].

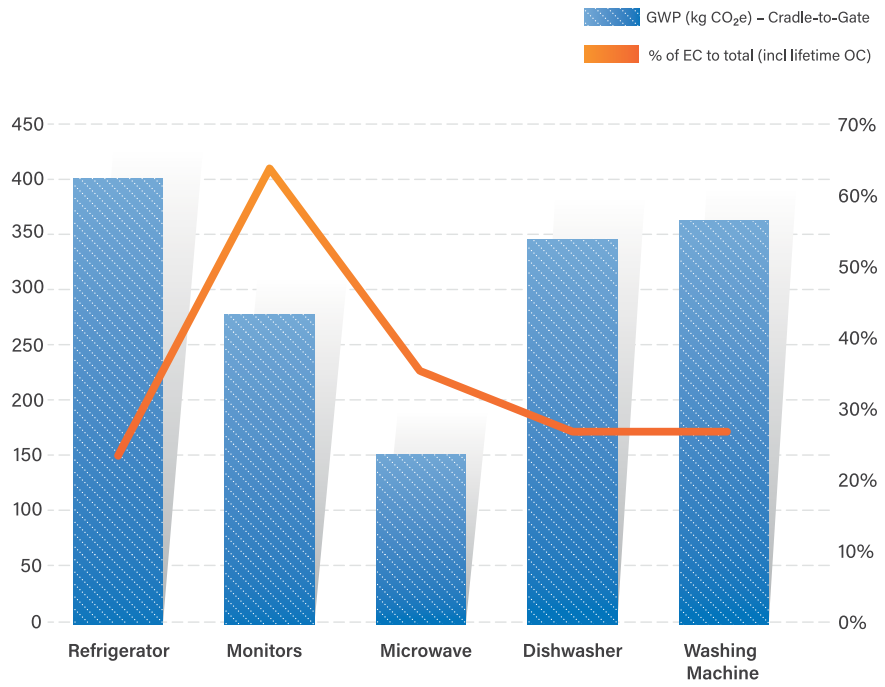
Microwave LCAs show comparable patterns. One study estimated lifetime emissions of 416 kg $CO_2e$ over eight years, with 36% attributed to embodied carbon [137]. Comparative LCAs of dishwashers and washing machines found lifetime emissions of approximately 1,330 to 1,375 kg $CO_2e$, with manufacturing contributing about 26% of total emissions, based on assumed lifespans of 12.5 and 10 years, respectively [41], [135]. These findings confirm that while operational energy use remains a major contributor, manufacturing emissions are significant and must be addressed.

Figure 18 visualizes the cradle-to-gate emissions of several common residential appliances alongside the percentage those emissions represent of total life-cycle GWP. The data confirms that while absolute embodied emissions vary, certain equipment types, particularly electronics with shorter service lives and lower operational demands, show a disproportionately high share of total emissions originating from manufacturing. Monitors, for example, have relatively modest energy use but high embodied carbon, which accounts for over 60% of their total GWP. In contrast, appliances like dishwashers and washing machines demonstrate higher operational impacts, with manufacturing contributing roughly one-quarter of their life-cycle emissions. These patterns underscore the importance of integrating embodied carbon into equipment standards, particularly for devices with shorter lifespans or limited operational emissions.

Data gaps remain particularly acute for smaller appliances and electronics. Available studies, while limited, show consistent trends. For example, analysis of mobile air conditioners found that embodied and end-of-life phases can contribute anywhere from 2% to 50% of total life-cycle emissions, depending on energy use intensity and product longevity [129]. Standardized data and consistent reporting for these equipment types remain scarce, limiting broader comparability across systems and regions.

**Figure 18: GWP Emissions for Residential Equipment and Appliances**

*Product stage embodied carbon (A1 to A3) of selected residential appliances, shown as total GWP in kg $CO_2e$ (blue bars, left axis), and as a share of total life cycle emissions including operational (orange line, right axis).*




Traditionally, wbLCAs exclude building service equipment and electrical and electronic equipment from their assessment boundaries, primarily due to limited data and inconsistent methodologies (see Figure 16) [18]. While data for small electronics remains fragmented, some progress has been made in standardized modelling of larger systems. RESNET Standard 1550 provides the most comprehensive North American dataset of embodied emissions for residential mechanical equipment [13]. While its material scope differs slightly from this research, it models a wide range of equipment types using A1 to A3 data drawn from EPDs, PEPs, and LCAs. Although refrigerant and gas emissions are excluded, RESNET Standard 1550 offers a valuable precedent for how embodied carbon in mechanical equipment can be systematically incorporated into wbLCA frameworks.

One of the most important takeaways from this research is the strong connection between operational and embodied emissions, particularly in heating and cooling systems. Equipment size scales with building load, and refrigerant charge scales with equipment size. Larger systems tend to have higher embodied emissions due to greater material intensity, including metals, plastics, circuit boards, and refrigerants. These impacts are further amplified by short product lifespans and frequent replacements. In contrast, better enclosures, passive strategies, and compact layouts reduce building loads, allowing for smaller, more efficient systems. These design choices lower emissions across the full equipment life cycle, especially when systems are properly sized and maintained to avoid premature replacement.

### 3.4.2 Refrigerant and Gas Emissions – Key Findings

Refrigerant emissions are among the most critical contributors to global GHG emissions [138], and often dominate the life-cycle emissions of equipment containing them, even when low-GWP options are used. These emissions occur across multiple life-cycle stages (manufacturing, installation, use, and end-of-life) and are driven by refrigerant type and charge, system design, leakage potential, and maintenance practices.

Refrigerants such as R410a (GWP 2,088 kg $CO_2e$/kg), R32 (677 kg $CO_2e$/kg), and R454B (466 kg $CO_2e$/kg) are particularly impactful due to their high GWP values and tendency to leak throughout the equipment lifespan [16], [139]. There are additional risks in manufacturing. For instance, R22 production can result in the creation of R23, a byproduct with an extremely high GWP of 14,800 kg $CO_2e$/kg [140]. This underscores the need to address emissions across the full refrigerant life cycle, from manufacturing through end-of-life [141], [142].

Research shows that poor refrigerant management, especially during the use and end-of-life stages, can significantly increase the embodied carbon footprint of HVAC systems [44]. Using CIBSE TM65 leakage assumptions (see Table 1), refrigerant emissions during the B-stage are the largest single source of emissions across all equipment scenarios in the MCE[2] study, even when using R32 in compliance with Ozone-Depleting Substances and Halocarbon Alternatives Regulations (ODSHAR). This is illustrated in a granular breakdown of emissions across life-cycle stages by equipment type in Figure 19.

System size and complexity strongly influence leakage risk. Larger systems like variable refrigerant flow (VRF) units, which require higher refrigerant charges and extensive piping, experience more leakage than compact, factory-charged packaged systems. TM65 reflects this distinction by assigning higher leakage assumptions to more complex systems [42]. Leakage assumptions also vary significantly across standards such as CIBSE TM65, ASHRAE 228, and the U.S. EPA's GHG Inventory Guidance, as summarized in Table 1. These inconsistencies directly affect emissions calculations, reducing comparability and reliability across different reporting frameworks.

**Figure 19: Life Cycle Emissions by Equipment Scenario**

*MEP $CO_2e$ emissions comparisons by life cycle stage, with R32 refrigerant. Note that emissions from leakage of fossil gas outside the building is not included and would alter the results of the analysis if included.*

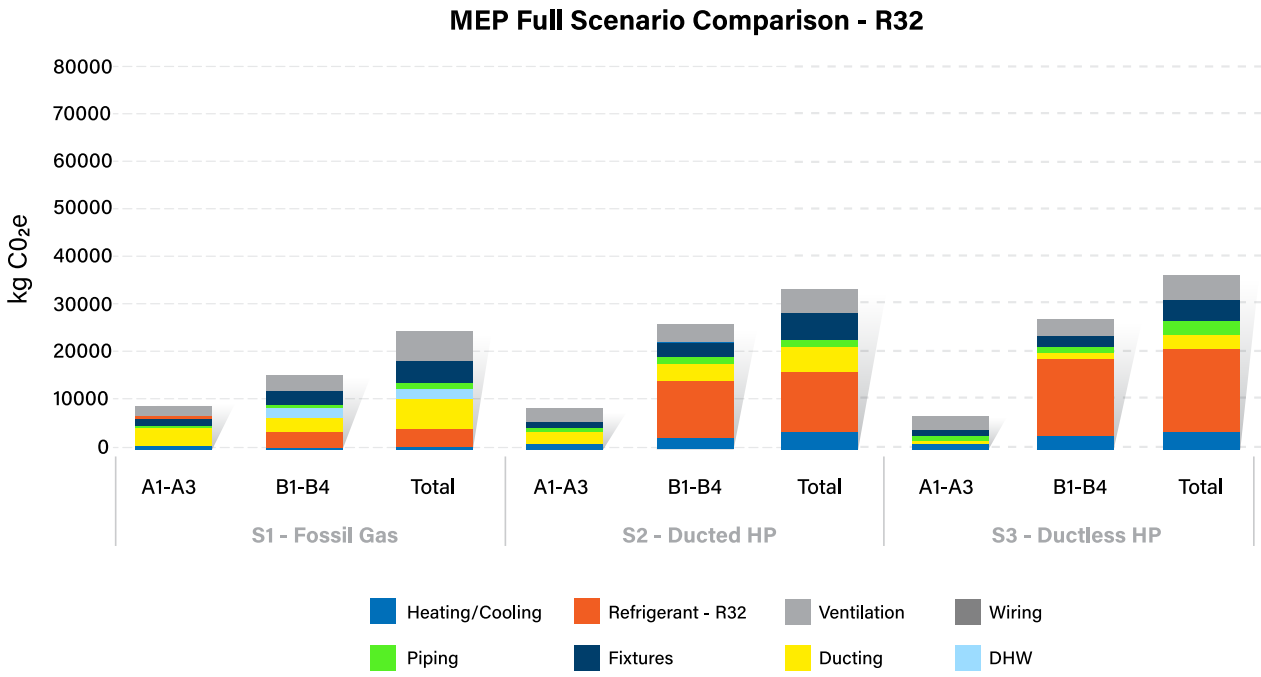


**Table 1:** Refrigerant leakage rate assumptions for residential HVAC equipment

| Standard | Leakage – Installation | Leakage – Use (annual) | Leakage – End of Life |
|---|---|---|---|
| **CIBSE TM65** | none attributed | 4% | 2% |
| **ASHRAE TM65NA** | none attributed | 1% – 5% | 20% |
| **U.S. EPA's GHG Inventory Guidance** | 1% | 10% | 20% |
| **ASHRAE 228** | none attributed | 2% | none attributed |
| **BREEAM** | none attributed | 6% | none attributed |
| **GHG Protocol** | 1% | 5% | 30% |

Mechanical contractors interviewed for this research confirmed that most operational leaks occur in distribution systems, with leaks in aging equipment cited as a major contributor. Improper recovery at end-of-life often results in full refrigerant loss, particularly in the residential sector where oversight is limited. By comparison, the embodied carbon of producing refrigerants is negligible—just 26 kg $CO_2$e/kg for R410a and 13 kg $CO_2$e/kg for R32, or roughly 1% to 2% of their GWP—making proper management of refrigerants (during installation, equipment operation, and end-of-life stages) far more critical [143].

Across the equipment life cycle, emissions risks vary by stage. During manufacturing, pre-charged systems carry some risk of leakage, though manufacturers report it as minimal. According to mechanical contractors, installation risks are relatively low when best practices are followed, although leaks can still occur due to poor workmanship or damaged components. Use-phase leakage poses the greatest risk; pinhole leaks, distribution piping failures, and aging components contribute to ongoing leakage. Mechanical contractors confirmed these risks, particularly in complex installations. End-of-life remains a critical emissions point, where poor refrigerant recovery frequently leads to full loss into the atmosphere. A California study identified that 80% to 99% of refrigerants from residential HVAC equipment are lost to the atmosphere at end-of-life, highlighting end-of-life management for refrigerant-based residential equipment as a major emission source [16].

Ultra-low GWP refrigerants such as R290 propane (GWP 0.02) and $CO_2$ R744 (GWP 1) are used in niche applications but face adoption barriers due to flammability, technical performance limits, and restrictive codes for residential heat pumps [43], [144]. Even "next generation" refrigerants like R32 and R454B carry moderate GWP values and are classified as A2L (mildly flammable), introducing new fire safety, design, and compatibility challenges. While R744 is used in specialty refrigeration products, its broader use in residential heat pumps remains constrained. Performance variability and replacement refrigerant compatibility with existing equipment also influence adoption. Reports like the California Public Utilities Commission's *Roadmap for Accelerating the Adoption of Low-GWP HVAC Refrigerants* and related manufacturer literature explore these complexities in detail [16], [145], [146].

Over a building's lifespan, HVAC systems undergo multiple installation and replacement cycles, each adding embodied carbon and increasing refrigerant leakage risks, especially in larger, more complex systems with higher refrigerant charges. Smaller, low-load systems inherently require less refrigerant, reducing both leakage and the embodied carbon of future replacements. This link between building energy performance and equipment-related emissions underscores the importance of integrating architectural design, energy modelling, and equipment specification.

By prioritizing low-load, high-performance strategies early in design, refrigerant-related emissions can be significantly reduced alongside operational carbon, offering a dual benefit often under-recognized in decarbonization policy.

Tools and methodologies for refrigerant emissions reporting, as identified in section 2.4, are becoming increasingly available, reflecting a broader industry shift toward transparency and reduction. While the U.S. *AIM Act* and Canada's ODSHAR phase down high-GWP refrigerant use in North America, they do not fully address leakage risks, system complexity, or poor end-of-life recovery [142], [49].

As outlined in Canada's *Green Buildings Strategy*, heat pumps are central to the decarbonization of the residential sector. As the market shifts away from combustion and electric resistance systems, the use of refrigerant-based technologies is rapidly increasing. While this reduces operational emissions, it raises the risk of fugitive emissions—unintentional refrigerant releases during manufacture, operation, servicing, or disposal. Given the high GWP of many refrigerants, even minor leaks can significantly increase a building's overall carbon footprint.

Scaling heat pump adoption increases the cumulative volume of refrigerants in circulation, magnifying the importance of proper handling at every stage. Without more stringent standards for installation, servicing, and decommissioning, unmanaged refrigerant leakage could offset the operational savings from electrification. Proactive measures, like increased contractor training, accreditation, and regulatory oversight, represent a critical opportunity to manage this growing risk as the residential equipment market transforms.

To address these risks, in addition to responding to regulatory requirements capping high-GWP refrigerants by switching to lower-emission refrigerants, public–private research partnerships like the EARTH Consortium are advancing refrigerant management solutions, next-generation low-GWP technologies, and improved training for contractors and manufacturers [147].

#### 3.4.2.1 Gas Considerations

Emissions from fossil gas (also known as "natural gas," referred to in this report simply as "gas") leaks are a significant concern. Methane, the primary component of gas, has a GWP of 25 kg $CO_2e$ [148]. Fugitive gas emissions may account for up to 25% of all anthropogenic GHG emissions (when using a conservative 2.7% infrastructure leakage rate). Most of this leakage occurs upstream, throughout the production and distribution chain [149].

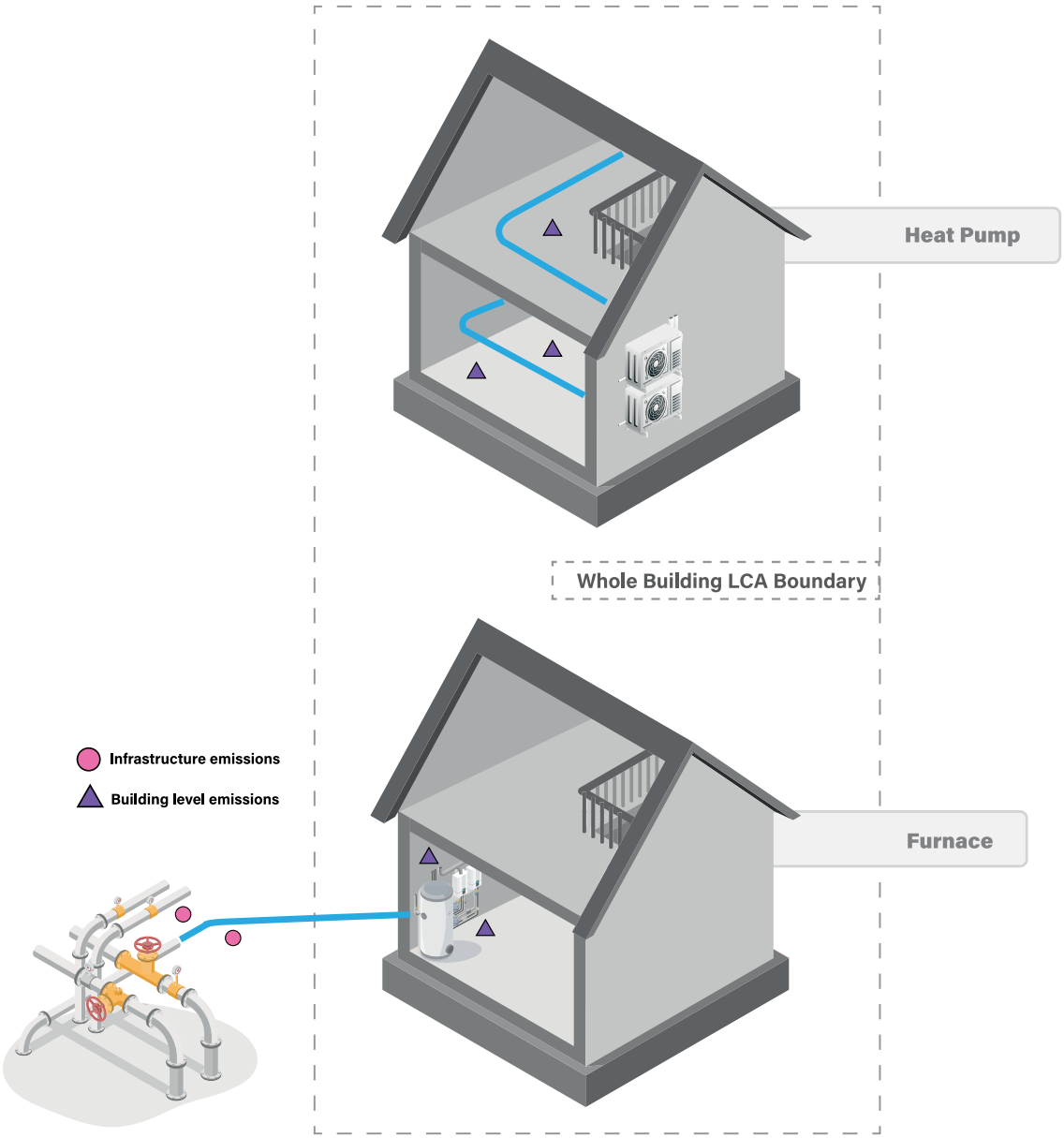
While rigorous safety standards reduce leakage risk at the building level [150], these infrastructure-based emissions are not captured in wbLCAs, as they fall outside the system boundary of the building. Despite this, building-level gas appliances, such as furnaces and water heaters, are dependent on this infrastructure. The gas that leaks upstream is destined for use in these systems. While attribution of upstream emissions to specific buildings is not standard practice, the causal link is clear: without end-use demand, these emissions would not occur.

The steady market transition from gas-based to refrigerant-based equipment introduces a significant challenge for comparative emissions accounting. In wbLCA practice, refrigerant emissions are included within the system boundary, while upstream gas leaks fall outside of the boundary (see Figure 20). As a result, refrigerant-based systems can appear more emissions-intensive within the boundaries of wbLCA, even when they replace infrastructure tied to substantial methane emissions. A new electric heat pump system replaces not only the gas-powered equipment itself, but also the connection to the broader gas infrastructure—and, with it, a proportion of the upstream emissions associated with gas extraction, transmission, and distribution.

This research does not quantify upstream gas emissions, but it acknowledges their relevance. This highlights the importance of identifying and managing the climate impact associated with gas infrastructure and underscores the need for improved methodologies that better reflect the full emissions picture. Further research and regulatory action will be required to reduce fugitive emissions throughout the gas supply chain.

**Figure 20: Boundary Gaps in Accounting for Equipment Emissions**

*Upstream emissions from gas infrastructure fall outside whole-building LCA boundaries, while refrigerant emissions from electric heat pumps are included. This asymmetry in system boundaries can obscure the climate benefits of switching from gas-based to electric equipment, even when the latter displaces infrastructure tied to significant methane leakage.*



### 3.4.3 Equipment Lifespan and Replacement Cycles – Key Findings

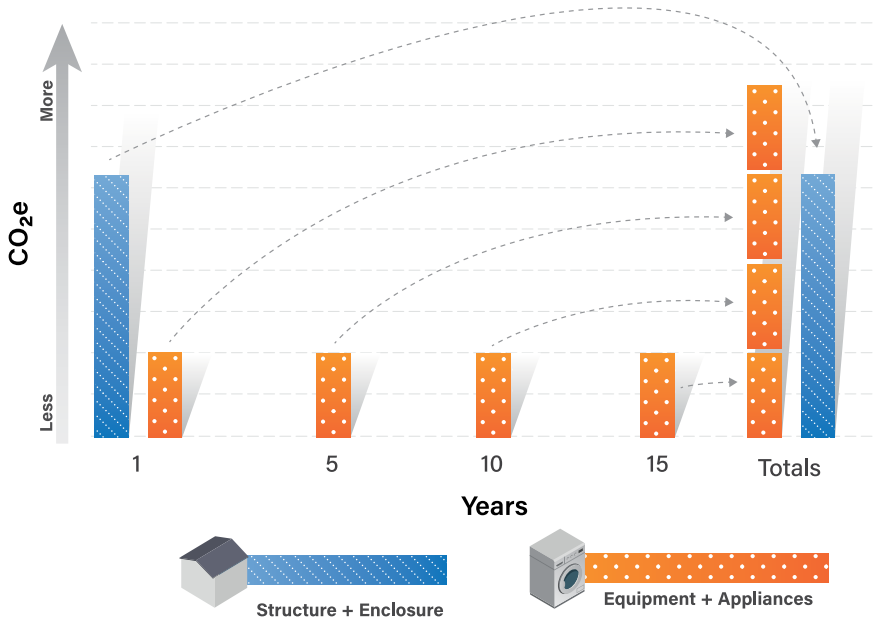
The lifespan of residential equipment plays a critical role in determining its cumulative environmental impact. Lifespan is not just a durability issue; it is an emissions issue, and one of the most overlooked in current equipment standards. Short service lives lead to multiple replacement cycles over a building's lifespan, amplifying emissions by repeating the embodied carbon costs of manufacturing, transportation, and disposal [101]. These impacts extend across the full life cycle of equipment, from A1 to A3 manufacturing through to end-of-life stages (C1 to C4), with each new replacement adding further burden. Research shows that over a building's full lifespan, the cumulative emissions from multiple replacements of MEP systems and tenant improvements can rival or even exceed the embodied carbon of a building's structure or enclosure [6] (see Figure 21). As product lifespans get shorter, embodied carbon emissions grow, virgin resource extraction increases, supply chain transport emissions multiply, and disposal volumes rise [151].

This pattern is particularly concerning for electrical and electronic equipment, where average product lifespans have declined sharply. For instance, the average microwave now lasts just 6.5 years [137]. The broader trend across consumer electronics shows declining product lifespans, accelerating the turnover of high-emission materials such as circuit boards, displays, and batteries [152]. For other small electronics, such as monitors, embodied emissions can account for more than 60% of total life-cycle emissions, emphasizing the significant role of production impacts relative to use. Limited repairability and non-modular design further compound these impacts by making component-level repair difficult, often resulting in full equipment replacement for even minor failures [153]. Longer-lasting equipment spreads its production impacts over more years of use, making durability an effective strategy for reducing embodied emissions [41].

Service life is a key factor in emissions calculations, and most PCRs specify Reference Service Life (RSL) values for different types of equipment. For instance, air conditioners are typically assigned a 20-year RSL,

**Figure 21: Cumulative Impact of Short Equipment Lifespans**

*Short equipment life cycles lead to repeated replacements, compounding embodied emissions over time. This illustration shows how the cumulative impact of equipment and appliance replacements can, over a typical building lifespan, rival or even exceed the embodied emissions of the structure and envelope.*



while water dispensers are given seven years [155], [156]. The importance of reporting lifespan data in GWP assessments is underscored by the methodology outlined in TM65. The TM65 Basic Calculation method—designed to simplify equipment emission reporting in lieu of EPD data—requires service life as one of only four core data inputs. If manufacturer data is unavailable, the method defaults to standardized estimates from resources like CIBSE Guide M [157].

Reference service life data is more readily available for HVAC equipment. ASHRAE lists water heaters as having service lives of between 15 and 35 years, fan coil units of between 15 and 20, and heat pumps of roughly 15 [15]. The ASHRAE HVAC Service Life Database offers further detail, although its coverage leans toward commercial systems. For residential applications, estimates for air conditioners and split systems are for 15 years, with window units closer to 10 [14]. Heat pumps, specifically residential air-to-air models, also have a typical service life of 15 years. For air handling units, which are more common in commercial settings, the database reports a service life of approximately 25 years [14].

These resources provide a useful baseline for mechanical equipment, and better alignment between PCRs, TM65, and reference data could strengthen the integration of lifespan into embodied carbon reporting. However, major gaps remain—particularly for non-HVAC residential equipment, including but not limited to, electrical and electronic equipment. The absence of standardized reporting for these products limits the accuracy of emissions assessments over multiple replacement cycles, making it difficult to account for their true impact across the building life cycle. Standards such as EN 50693, *Product category rules for life cycle assessment of electrical and electronic products and systems,* offer a framework for LCA, and environmental declarations for electronic and electrical products and could serve as a model for more consistent reporting across non-HVAC equipment categories [158].

Repairability is another important factor that influences equipment lifespan and replacement. This allows for the replacing of failed components rather than discarding entire units. Equipment failures, especially in components like circuit boards, displays, or sensors, may lead to early disposal, even when the majority of the unit is functional. The Fairphone, a modular smartphone that incorporates opportunities for repair through replaceable batteries, screens, and other parts, offers a compelling counterexample. By making repairs easy and accessible, the company aims to reduce both material waste and embodied emissions. This example highlights a broader trend toward modular design, spare parts availability, and ease of disassembly, aligning with the goals of the circular economy [159]. Similar modular strategies could extend the life of home appliances and electronics but appear to remain underused in the residential sector.

End-of-life management also presents major challenges. Current recycling infrastructure is poorly equipped to handle composite materials and non-modular designs. Inconsistent disassembly protocols and limited manufacturer take-back support—in which a manufacturer "takes back" products from consumers at the end of product life for material recovery or remanufacturing—further limit recovery. Composite materials that cannot be disaggregated at end-of-life further increase the likelihood of more emission-intensive disposal scenarios and eliminate opportunities to reclaim and recycle high-impact metals. As a result, most equipment still ends up in landfill or undergoes energy-intensive processing that further contributes to emissions. An analysis of 100 discarded microwaves found that many units were discarded due to single sub-assembly failures, such as faulty capacitors or control circuits, that could have been repaired [137]. Without effective repair and recycling pathways, the environmental burden of short-lived equipment increases at every turn. Proprietary components, certification liabilities, and limited manufacturer support contribute to a system in which replacement is easier than repair, driving repeated manufacturing emissions.

Understanding and declaring equipment lifespan is essential to reducing emissions tied to material resource use, equipment longevity, and replacement cycles. While broader circular economy strategies are beyond the scope of this research, equipment lifespan has a direct, measurable impact on emissions and must be reflected in any emissions-focused approach to standards development. Integrating lifespan into

standards—through reporting requirements, shared reference values, and support for repairability and modular design—is a positive step toward building an emissions-literate equipment ecosystem that values durability, circularity, and climate performance in equal measure.

### 3.4.4 Implications for Standards Development

Decarbonizing residential equipment is both necessary and achievable, but it requires a coordinated framework that connects regulation, industry, and market transformation. Standards can assist in providing this alignment by offering consistent methodologies, reducing uncertainty, and supporting clear compliance pathways. Although embodied carbon is beginning to appear in commercial procurement policies and whole-building assessment frameworks, residential equipment remains a major omission.

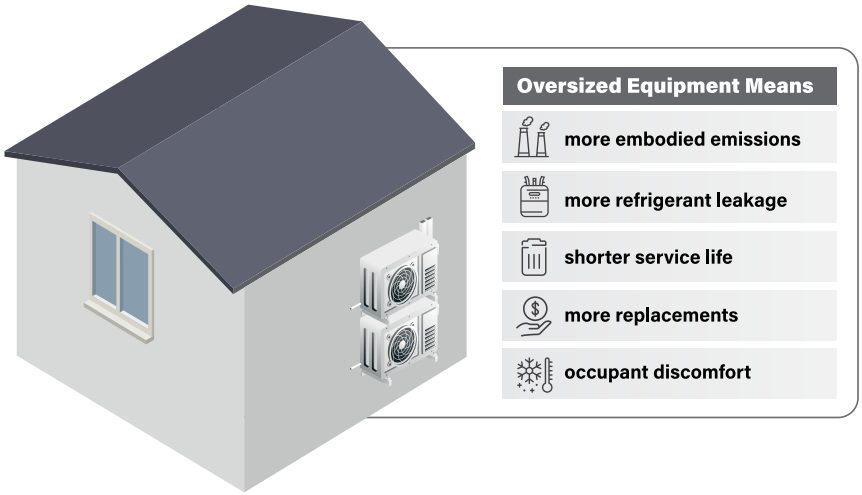
An interview with a mechanical contractor illustrated the limitations of current standards. They described the difficulty of applying CSA F280, *Determining the required capacity of residential space heating and cooling appliances,* Canada's national method for calculating heating and cooling loads, to residential projects. Many homes are exempt from load calculations, and as a result, equipment can often be oversized. This leads to higher refrigerant use, reduced service life, and more frequent replacement. In effect, oversized systems increase emissions across the board, including operational, refrigerant, and embodied impacts (see Figure 22).

Connecting mechanical design standards with emissions-focused product standards creates an opportunity to address these issues more effectively. When standards reflect the relationship between energy loads, system sizing, and product-level emissions, they can support better design decisions, smoother implementation, and measurable reductions in both operational and embodied carbon. This is not a series of separate problems, but a shared opportunity to build one coordinated solution through standards development.

Developing standards that incorporate embodied carbon metrics, refrigerant considerations, and service life expectations will be essential for meeting national and global emissions targets. This shift can also support product differentiation, improve supply chain resilience, and enable transparent communication through

**Figure 22: Cumulative Impact of Short Equipment Lifespans.**

*Oversized HVAC equipment leads to a host of problems related to energy and performance of the equipment, as well as a similar host of problems related to embodied carbon. Strategies to ensure right-sizing of equipment, especially in low-load homes, results in widespread benefits in comfort, energy, cost, and GHG emissions.*



standardized disclosure and labelling. Without this progress, emissions from residential equipment will continue to go unaccounted for, slowing Canada's climate efforts. But with the right tools and coordination, these impacts can be addressed together through an integrated standards approach that accounts for the full life cycle of residential equipment.

## 3.5 Standards Evaluation

Standards evaluation reveals a significant gap in the calculation and reporting of embodied carbon for residential equipment. Industry parties interviewed for this research, including manufacturers, policy makers, builders, and mechanical contractors, emphasize the need for standardized methodologies that ensure consistency, accuracy, and predictability in embodied carbon assessments.

A wide range of standards were reviewed as part of this evaluation, many of which did not include the emissions, lifespan, or end-of-life information sought by this research. A full list of these reviewed standards is included in Appendix B.

### 3.5.1 Canadian Standards

A review of Canadian standards for residential appliances shows that they largely prioritize product performance, installation practices, and operational energy efficiency, with minimal attention to embodied carbon or full life-cycle impacts. Material efficiency, repairability, product lifespan, and end-of-life considerations are generally absent.

Insights from industry interviews reinforce these findings. Representatives of contractor trade associations interviewed for this research identified a significant gap in standardization around embodied carbon. They emphasized that professionals in the field are actively seeking standards and technical guidance to navigate regulatory changes and market opportunities, as well as to level the playing field across compliance and best practices across the industry. Contractors expressed a need for greater transparency, improved access to embodied carbon data, and standardized methodologies to align with emerging regulations, as well as stronger regulations to compel practitioners to comply with the standards. Without clear standards, they face challenges in responding to new regulatory requirements and market shifts toward low-carbon solutions.

An interview with a standards professional further confirmed that end-of-life considerations for residential equipment are not currently addressed in Canadian standards, aside from niche areas like nuclear materials and fuel tank decommissioning. While nuclear decommissioning is highly specialized, the fuel tank example offers a potential precedent for developing end-of-life requirements in the residential equipment context [160].

Despite these gaps, Canada has demonstrated partial alignment with international frameworks by adopting several ISO 14000-series standards related to environmental management, LCA, and eco-labelling. These standards offer a foundation for further integration of embodied carbon and life cycle considerations into Canadian codes and product standards.

CSA Group has recently announced the co-development of a new bi-national standard with ASHRAE for sustainability assessments of MEP products. The standard will establish a process for creating LCA-based product claims for MEP assemblies, including developing or adopting PCRs, conducting LCAs, publishing product claims for public access, and updating assessments as needed.

This standard supplements ISO 14025 *Environmental labels and declarations,* and is intended for use when existing product claims are unavailable or incompatible with documentation requirements. While this will help fill data and process gaps for MEP systems, it does not cover all equipment in scope, most notably, home appliances and electronic equipment.

Previous efforts to embed life-cycle thinking into Canadian appliance standards can be seen in the UL/AHAM/CSA 7000-series, which incorporated limited sustainability criteria. However, this series is now being withdrawn. Its existence, although short-lived, demonstrates that integrating life-cycle principles into Canadian standards is feasible and can be built upon in future updates.

### Codes and Performance Standards

Standards such as CSA C22.2, and the associated code CSA C22.1, establish essential requirements for electrical safety in residential equipment [161], [162]. While these documents help ensure compliance with fundamental performance and design criteria, environmental impacts are out of scope. The standards therefore do not address product longevity, emissions associated with material selection, and considerations related to premature obsolescence or repairability.

Construction and performance standards for residential equipment are primarily concerned with providing requirements for verifying that products meet baseline functional requirements. These normative standards help ensure that appliances like refrigerators maintain safe internal temperatures and that systems such as heat pumps effectively provide heating and cooling under specified conditions. While essential for user safety and product reliability, these normative standards do not account for embodied carbon, service life variability, or environmental performance. One limited exception is the electric storage tank water heater standard [163], which includes a mention of product life expectancy. However, this reference is not part of a broader framework for evaluating service life or life-cycle emissions and remains an outlier among product standards.

### Energy Efficiency Standards

Energy efficiency remains a central focus of Canadian regulations, with standards such as CAN/CSA-C300-15, *Energy performance and capacity of household refrigerators, refrigerator- freezers, freezers, and wine chillers,* CAN/CSA-C361-12, *Test method for measuring energy consumption and drum volume of electrically operated household tumble-type clothes dryers,* and CAN/CSA-C815-09, *Energy performance of drinking water coolers,* setting minimum performance thresholds for residential appliances [164], [165], [166]. Programs like EnerGuide and ENERGY STAR complement these requirements through mandatory and voluntary labelling that guide consumer decisions and recognize products that exceed baseline efficiency standards [167].

While effective in reducing operational emissions (Scope 2), these standards and programs do not address embodied carbon, durability, or product lifespan. There remains an opportunity to connect efficiency with broader climate and economic goals.

### Refrigerant Codes and Standards

CSA B52:23, *Mechanical Refrigeration Code,* establishes safety and containment requirements for refrigerants, focusing on risk mitigation during operation and servicing [168]. CSA C22.2:120, *Refrigeration Equipment,* is a standard that applies to refrigeration equipment, which includes requirements for electrical features and the mechanical safety of refrigeration systems [169]. These codes and standards are designed primarily to protect health and safety rather than manage GHG emissions. They do not require reporting of refrigerant-related carbon impacts or include LCA methodologies. Given the high global warming potential (GWP) of many refrigerants, this represents a significant gap in addressing the full environmental footprint of refrigerant-based residential equipment.

Canada has also implemented the *Environmental Code of Practice for the Elimination of Fluorocarbon Emissions from Refrigeration and Air Conditioning Systems* [139]. This document outlines best practices for refrigerant handling, including leakage prevention, servicing protocols, and end-of-life disposal. However, it also falls short of integrating embodied carbon accounting or life-cycle based emissions tracking associated with refrigerant management.

### Gas Code and Standards

As with refrigerants, Canadian standards for gas systems prioritize quality and health and safety in equipment manufacturing, installation, maintenance, and repair. Some relevant standards include CSA B149.1:25, *Natural Gas and Propane Installation Code,* CSA/ANSI Z21.10.1:19/CSA 4.1:19 *Gas Water Heaters,* CSA/ANSI Z21.24:22 / CSA 6.10:22 *Connectors for Gas Appliances,* and others governing gas dryers, regulators, and shut-off devices [154], [170], [171], [172], [173], [174]. These standards include rigorous leakage management protocols due to the flammability of fuel gas. However, they do not address GHG emissions. No emission assessment or reporting requirements currently exist within building-level Canadian standards for gas equipment or distribution systems.

As noted in previous sections, fugitive methane emissions from gas distribution infrastructure are a known contributor to national GHG totals. Although these emissions occur beyond the building boundary and are not within the formal scope of this study, they represent a significant source of untracked emissions and are noted as an area for future consideration in the Recommendations section.

### Sustainability Standards

The CSA 7000 series, developed in collaboration with The Association of Home Appliance Manufacturers (AHAM) and UL Solutions, incorporated sustainability considerations into residential appliance standards. This family of standards includes guidance on refrigerators, portable and floor care appliances, clothes washers, and cooking appliances. The series assesses environmental performance based on materials, energy use, manufacturing practices, durability, end-of-life management, and innovation [130], [131], [132], [133]. Grounded in LCA principles, the series emphasized emissions reduction but lacked explicit embodied carbon accounting and standardized service life reporting.

These standards have since been withdrawn and are no longer referenceable in either methodology or guidance. However, their development set a precedent for integrating sustainability into residential equipment standards by embedding life-cycle emissions criteria into product standards.

CSA S478:19, *Durability in Buildings,* is a building-related standard that offers frameworks for defining service life and material performance, and it could be extrapolated to residential appliances and equipment [175]. Similarly, CSA Z782-06, *Guideline for Design for Disassembly and Adaptability in Buildings* introduces concepts that could inform appliance and equipment design for easier repair, reuse, and recycling [176]. Notably, these Canadian guidelines helped shape ISO 20887:2020, *Sustainability in buildings and civil engineering works – Design for disassembly and adaptability – Principles, requirements and guidance,* positioning the country as a leader in advancing circular design practices.

## 3.5.2 International Standards

A review of international standards highlights an increasing emphasis on life-cycle carbon assessments, embodied carbon measurement, and circular economy principles within regulatory frameworks for building systems and residential equipment. While many standards historically focused on operational energy efficiency and refrigerant safety, recent efforts have expanded their scope to address material efficiency, emissions tracking, and end-of-life considerations. These frameworks offer methodologies that could inform future Canadian standards development.

### Foundational Standards for LCA and Carbon Accounting

International standards form the foundation of credible life-cycle and carbon footprint assessments for residential equipment. Several key standards underpin the methodologies referenced throughout this research. ISO 14040 and ISO 14044 establish the broader principles, framework, and methodological requirements for conducting LCAs across all stages of a product's life, ensuring consistency and credibility in emissions accounting [177], [178].

EN 15978, although a European standard, is internationally recognized as the most advanced framework for assessing the environmental performance of buildings [123]. It provides the basis for major tools such as the Royal Institution of Chartered Surveyors Professional Standard and NRC guidelines in Canada. Any wbLCA intended to integrate residential equipment emissions should ensure alignment with this standard.

ISO 14025 sets the principles and procedures for developing Type III environmental declarations, including EPDs and PEPs, ensuring transparency and comparability in environmental reporting [179]. For electrical and electronic products, EN 50693 establishes PCRs and LCA methodologies specific to the sector [161]. It defines requirements for LCA reporting and service life assumptions, providing a structured framework for developing standardized environmental declarations for residential electronic equipment.

ISO 14067 provides detailed requirements and guidelines for quantifying the carbon footprint of products, offering a critical alignment point for embodied carbon reporting across residential equipment categories [180].

Additional standards offer important guidance on more specialized aspects, like lifespan requirements. ISO 15686 provides a structured international framework for the service life planning of buildings and components [181]. It includes RSL values, life-cycle costing, and methods for integrating durability and repairability into environmental assessments. This standard supports consistent use of RSL data in EPDs and LCAs, offering a model for incorporating longevity into residential equipment standards.

### Whole Building LCA Methodologies

Efforts to integrate embodied carbon and LCA methodologies into international standards are increasing. The draft ASHRAE Standard 240p (currently in development) introduces a methodology for quantifying both embodied and operational GHG emissions in buildings, including MEP systems and their impacts as discussed previously, at a commercial scale.

At the residential scale, RESNET Standard 1550 (currently in development in the U.S.) provides a methodology for assessing embodied carbon emissions in residential buildings, including the A1 to A3 emissions of MEP equipment, using data collected by energy raters (trained professionals who evaluate home energy performance through programs such as the Home Energy Rating System (HERS) Index [13]. The standard is expected to be finalized and published by the beginning of 2026 and is anticipated to become an ANSI standard shortly after publication, supporting its potential adoption or adaptation within Canadian contexts.

This standard acknowledges the significant differences in project delivery between residential and non-residential projects, including design software accessibility, architectural service availability, and technical knowledge and resources. A methodology that leverages the current infrastructure of the energy adviser's role in residential building performance assessment allows a pathway for scaling embodied carbon assessments specifically for this sector of the building industry and provides a standards-based context for implementing equipment-specific standards.

### Product LCA Methodologies

Frameworks such as CIBSE TM65 and ASHRAE TM65NA offer standardized methodologies for measuring the embodied carbon of mechanical equipment in lieu of EPDs. Notably, none of these standards is applicable to electrical and electronic equipment, and are restricted to the estimation of emissions from building service (MEP) equipment only. However, LCA experts interviewed for this research indicate that these methodologies could be applied to electrical and electronic equipment with further research.

### U.S. State Energy Code

In the U.S., Vermont has taken steps to integrate embodied carbon into its state energy code by including embodied emissions in the points-based prescriptive compliance path. Projects can earn points for using low-embodied carbon insulation, helping ensure that code-driven increases in insulation levels don't unintentionally increase embodied emissions [182]. Massachusetts recently adopted a similar approach in its energy stretch code, where low-carbon insulation can reduce a project's HERS index, one of the state's recognized energy code compliance tools [183]. While these policies do not yet address residential equipment, they reflect the same dual-emissions consideration introduced in Section 3.4.1, recognizing that materials and systems can impact both operational and embodied carbon. These examples offer a clear precedent for extending regulatory frameworks to include equipment, especially as it sits at the intersection of energy performance and life-cycle emissions.

### Certification Programs

Examples of frameworks that integrate EPD collection and transparency requirements include LEED v5, which incorporates EPD documentation into its certification process [91]. As LEED has evolved from a voluntary program to a compliance pathway in some jurisdictions, it has driven greater market demand for EPDs and

related product performance disclosures, such as Health Product Declarations (HPDs). This illustrates how standards can support policy development, increase transparency in material data, and encourage manufacturers to improve product impact reporting. Although these programs are more widely adopted in commercial markets, they remain relevant and applicable to residential contexts.

**Refrigerant Management and Emissions Tracking**

Several international standards address refrigerant classification, safety, and leakage tracking, although their focus on carbon impacts varies. ISO 5149 addresses safety and environmental requirements for refrigerating systems, covering leakage prevention and refrigerant recovery practices essential to managing high-GWP refrigerants across the product life cycle. ANSI/ASHRAE Standards 15 and 34 classify refrigerants and establish safe handling guidelines, but they do not systematically account for the GWP or life-cycle emissions of refrigerants [184], [185]. In contrast, CIBSE TM65 and ASHRAE TM65NA provide methodologies for estimating refrigerant leakage emissions through a calculation methodology that refers to included refrigerant GWP factors and manufacturer-provided lifespan data. The forthcoming development of ASHRAE 196 will provide guidance on refrigerant leakage testing for equipment, addressing leakage at that portion of the product life cycle. Whereas much of the refrigerant management and leakage occurs in the field in association with distribution system installation and end-of-life decommissioning, this standard will support leakage reduction and management of the equipment itself during the manufacturing process.

**Circular Economy and Product Durability**

International sustainability policies increasingly emphasize durability, repairability, and material recovery as key strategies for reducing environmental impacts. The EU *Circular Economy Action Plan* outlines regulatory mechanisms to minimize premature obsolescence by promoting product longevity, repairability, and material reuse. A major policy milestone within this initiative is ESPR. ESPR establishes requirements for embodied carbon reduction, repairability standards, and material efficiency, setting a high benchmark for integrating circular economy principles into product standards. The Restriction of Hazardous Substances Directive is a long-standing EU policy that addresses proper management of electrical and electronic equipment disposal and waste management to safeguard against toxicity impacts, which is indirectly related to the environmental impacts of GHG emissions [186].

### 3.5.3 Leveraging International Standards and Databases

International standards increasingly incorporate life cycle carbon accounting alongside operational efficiency requirements, reflecting a broader shift toward comprehensive environmental performance metrics. Foundational ISO and EN guidelines, such as ISO 14067, *Greenhouse Gases – Carbon Footprint of Products,* and EN 15978, *Sustainability of Construction Works,* offer widely recognized frameworks for environmental labelling, embodied carbon assessment, and life-cycle analysis, many of which have already been adopted by Canadian standards organizations.

Where gaps in Canadian standards persist, international frameworks such as ASHRAE TM65NA, *Embodied Carbon in Building Services: A Calculation Methodology for North America,* and the EU's ESPR offer valuable precedents. ESPR, in particular, provides a model for how Canada could embed circular economy principles into residential equipment regulations and align with broader global efforts to reduce emissions, improve resource efficiency, and enhance product transparency.

In Canada, building and energy codes have potential to be an important mechanism to address embodied carbon in residential construction, including for MEP equipment. Procurement policies, such as Buy Clean, still prioritize large-scale projects and high-impact materials like concrete, but emerging alignment opportunities exist through evolving product category rules, international LCA standards, and regional tools like TM65 and TM65NA, which could support integration into future Canadian equipment standards and code frameworks.



**"International frameworks provide both technical guidance and policy precedents that could support the development of Canadian standards to advance emissions transparency, life-cycle alignment, and circularity across residential equipment categories."**

Where EPDs are not available, interim methodologies like TM65NA provide practical pathways for estimating embodied carbon using secondary data and proxy calculations. Although originally developed for MEP systems, these tools could be adapted to a broader range of residential equipment and serve as useful transitional strategies while manufacturers work toward full LCAs and EPD generation. Databases such as PEP Ecopassport and ÖKOBAUDAT further support standardized environmental impact assessments by offering detailed life cycle inventory data on resource consumption and manufacturing emissions, improving the accuracy and consistency of estimates across life-cycle stages and product categories.

Emerging policies, including Vermont and Massachusetts energy codes and standards such as RESNET 1550, demonstrate how embodied carbon considerations can be embedded within existing building and energy code frameworks. Robust education and training programs will also be essential to ensure that standardized methodologies are widely adopted and consistently implemented across jurisdictions.

Collectively, these international frameworks provide both technical guidance and policy precedents that could support the development of Canadian standards to advance emissions transparency, life-cycle alignment, and circularity across residential equipment categories.

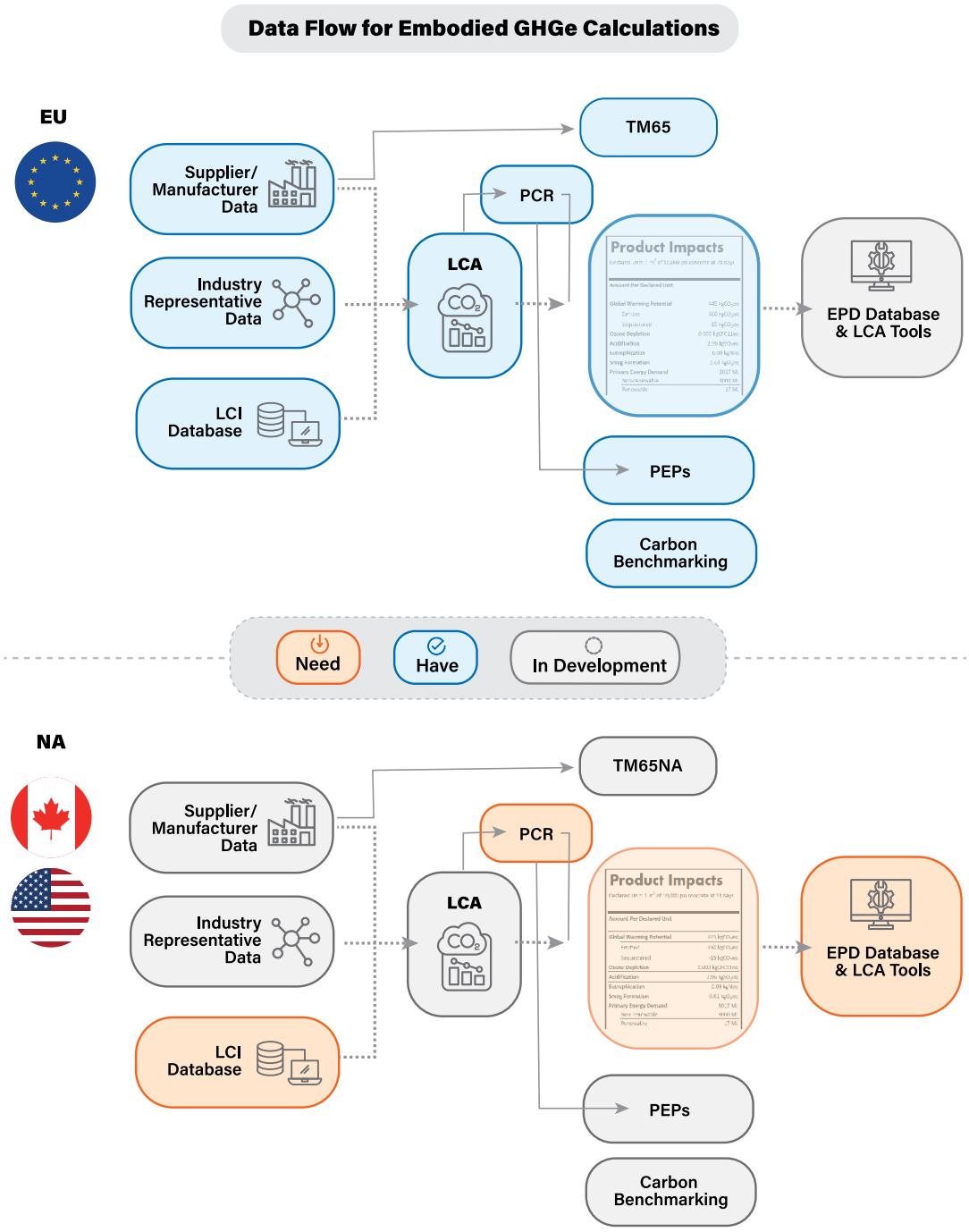
# 4 Evidence-Informed Recommendations to Address Gaps

## 4.1 Overall Gaps Identified

Efforts to reduce the environmental impacts of residential equipment face major barriers due to a lack of standardized data and consistent methodologies across the three critical impact categories identified in this research: embodied carbon, refrigerant and gas emissions, and equipment lifespan. While interest in emissions reduction is growing, available data is limited, fragmented, and often misaligned with the needs of building-scale LCA. Embodied carbon data is frequently incomplete or absent, particularly for small appliances and electronics, and rarely reflects North American manufacturing. Refrigerant emissions are significant but inconsistently estimated, with leakage rates and management practices varying widely across standards and regions. Lifespan data, meanwhile, is rarely disclosed in a transparent or standardized way, making it difficult to account for the emissions consequences of frequent equipment replacement. These gaps hinder accurate whole-building analysis, obscure emissions responsibility, and constrain the development of standards that could support emissions reduction across the sector.

**Figure 23: Regional Comparison of Embodied Carbon Data Systems**

*Comparison of data flow for embodied carbon calculations in the European Union (EU) and North America (NA). While the EU has established more key elements, including TM65, PEPs, and integrated benchmarking, North America still lacks key elements or has them in early development. This limits consistency, transparency, and comparability in residential equipment emissions reporting, and is a gap ready to be filled.*



### 4.1.1 Gaps in Standardized Embodied Carbon Data

Embodied carbon data for residential equipment remains fragmented, inconsistent, and incomplete across most product categories. While EPDs and PEPs exist for some mechanical systems, like heat pumps, air handling units, and motors, these largely originate from European sources and are not representative of North American equipment. Standardized environmental declarations for water heaters, refrigerators, and dishwashers are limited in North America and concentrated in the commercial sector, where LEED and other programs have historically shaped demand for product transparency as a prerequisite for data development.

Manufacturers interviewed for this research identified demand from these programs as a key justification for investing in product transparency documentation. In contrast, there is little comparable demand in the residential sector, limiting incentives for manufacturers to disclose emissions data.

A comparison of European and North American data infrastructure is shown in Figure 23, highlighting key gaps in North American methodologies and reporting tools.

The most significant data gaps are in small appliances (e.g., microwaves, dehumidifiers) and electronics (e.g., battery chargers, set-top boxes, thermostats), where there are virtually no standardized declarations. Where emissions data does exist, it comes from isolated LCA studies rather than standardized reporting. Lack of harmonized methodologies around system boundaries, functional units, and life-cycle stages makes comparisons difficult. For example, the only known LCA for microwave ovens omits production and end-of-life data. Other assessments for portable air conditioners or stoves are outdated, out of scope, or incomplete.

Available PCRs are also scarce. There was only one PCR for air conditioners; it was tied to two EPDs. There are two PCRs for water dispensers, although no matching EPDs were located. Three PCRs for electrical and electronic equipment were identified, but none were relevant to this study. LCA experts noted that slow PCR development stems from high costs, coordination complexity, and limited market demand. One manufacturer indicated that only the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) and ASHRAE have the capacity to support a North American HVAC PCR. While a joint bi-national ASHRAE/CSA Group MEP PCR project is underway, it is a lengthy process. Some European PCRs may be adaptable but require extensive modifications—similar to the adjustments made in the development of ASHRAE TM65NA—to suit North American testing and regulatory contexts.

Even when environmental declarations are available, inconsistencies in life-cycle stage coverage, particularly for end-of-life emissions, pose additional challenges and limit comparability. This issue is well documented in initiatives like the ECHO *Recommendations for Alignment* and the Carbon Leadership Forum's *End-of-Life Modeling and Data in North American Whole Building Life Cycle Assessment Tools.* These gaps are particularly problematic for short-lived equipment that may be replaced multiple times over a building's lifespan, compounding unreported impacts.

Europe has taken steps to standardize residential equipment data through initiatives like the EU Ecodesign directive and France's PEP Ecopassport system, particularly for HVAC and heat pump products. North America lacks the equivalent regulatory infrastructure, which has stifled data development and made product comparisons more difficult. This creates a compounding problem: without data, cross-market comparisons are difficult, and standardized reporting practices struggle to take hold.

Methodologies like CIBSE TM65 and ASHRAE TM65NA offer interim approaches for estimating MEP system emissions when EPDs are unavailable. These tools support greater consistency in wbLCA, but adoption is still limited. No public database of TM65NA-modelled values exists for residential equipment, and no similar estimation method is available for electrical and electronic equipment. Without such a tool, emissions data for electronics and small appliances will remain a persistent gap.

Most wbLCA frameworks require reporting across the full life cycle, but ISO-compliant EPDs often include only A1 to A3 emissions. This is particularly problematic for HVAC systems, which carry substantial impacts in B and C stages due to refrigerants, maintenance, and repeated replacements. If these stages are omitted, building emissions are underestimated. Frequent replacement cycles throughout the life of the building compound the importance of reporting full life-cycle emissions for this equipment. Robust reporting must include full life-cycle coverage and account for expected service life and replacement frequency, especially for equipment categories with short lifespans.

Finally, data transparency remains a major barrier. Even when emissions data is described as publicly available, access to full LCA reports is often restricted. For example, Société Générale de Surveillance (SGS) awarded Midea the world's first third-party–verified LCA certificate for a washing machine in 2023 [187]; however, the complete LCA remains unavailable, illustrating the lack of transparency in data-sharing and emissions reporting. Paywalls and proprietary tools limit the ability of researchers, practitioners and policy makers to evaluate, compare, or inform policy and procurement decisions with confidence.

### 4.1.2 Gaps in Standardized Refrigerant and Gas Emissions Data

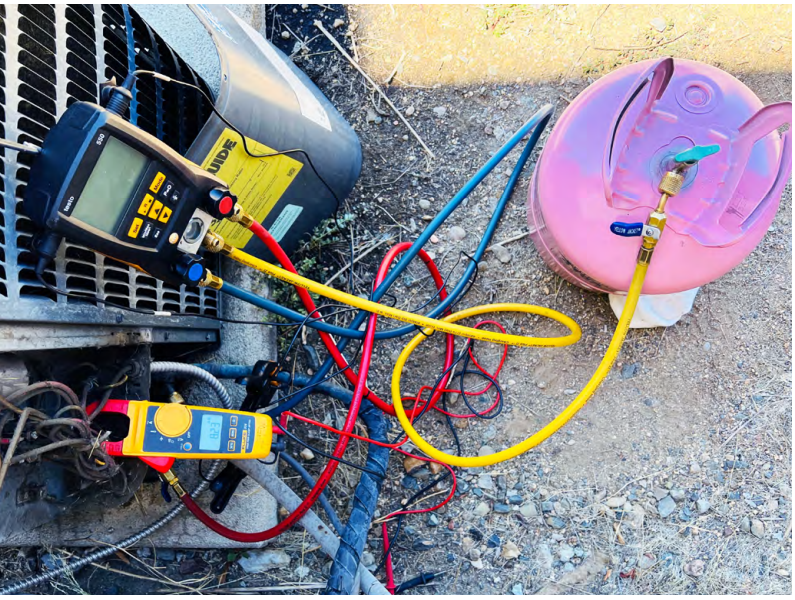
While the GWP of common refrigerants is well documented, estimating refrigerant leakage remains a major challenge. System charge quantities can be estimated using manufacturer software, but leakage assumptions vary widely across standards, limiting consistency and accuracy. Effective refrigerant management must address emissions throughout the equipment life cycle—from manufacturing and installation to operation, maintenance, and decommissioning. Inconsistent assumptions across standards can create large margins of error, weakening emissions inventories and performance-based policies. A more harmonized, evidence-based approach to leakage assumptions is needed to improve consistency in analysis and decision making.

Several initiatives aim to improve leakage data and testing protocols. ASHRAE Standard 196, now in development, will establish a method to test refrigerant leakage at the equipment level. The EARTH Consortium, introduced in section 3.4.2, is developing a supporting test facility to support validation against this standard. While focused on leakage during manufacturing and assembly, this work represents a key step toward improving upstream data. However, it does not address emissions during use or at end-of-life, both of which remain critical sources of refrigerant loss.

In Canada, refrigerant and gas regulations vary across the country and cannot be assumed to offer adequate mitigation from a climate perspective. These regulations can exclude smaller systems, leaving residential equipment under-regulated in some jurisdictions. Contractors interviewed for this research reported exemptions for residential refrigerant system installation requirements in some provinces and territories, allowing unlicensed personnel to install and repair equipment. This can result in under-charged systems, leaks, and premature failure.

Contractors also noted that refrigerant-based heat pump installation manuals are often the only available guidance for technicians. However, they described these manuals as occasionally incomplete, inaccurate, or poorly translated—insufficient for ensuring proper installation or leak-free performance. These manuals occasionally do not clearly reflect the requirements of the relevant equipment standards needed to support best practices in refrigerant management.

End-of-life emissions pose another major data gap. The GHG Protocol, a globally recognized standard for GHG accounting used by governments, businesses, and reporting frameworks, assumes a 30% refrigerant leakage rate at end-of-life for residential systems, underscoring the emissions risk from improper disposal. This applies to both field decommissioning and appliance disposal. Although the *Environmental Code of Practice for the Elimination of Fluorocarbon Emissions from Refrigeration and Air Conditioning Systems* and Heating, Refrigeration and Air Conditioning Institute of *Canada's Refrigerant Management Canada* program offer



**"Inconsistent assumptions across standards can create large margins of error, weakening emissions inventories and performance-based policies. A more harmonized, evidence-based approach to leakage assumptions is needed to improve consistency in analysis and decision making."**

guidance [139], [188], real-world implementation remains inconsistent, and full release of refrigerants at the unregulated end-of-life decommissioning of residential equipment is reported to be common. The gap between technical guidance, regulatory oversight, and real-world practices continues to drive fugitive refrigerant emissions from both mechanical systems and consumer appliances.

### 4.1.3 Gaps in Standardized Lifespan Reporting

One of the clearest findings of this research is that product lifespan data is rarely reported in a consistent or transparent way. Despite its importance for estimating equipment-related emissions, few manufacturers provide clear disclosures on expected service life. Warranties are often the only product-specific reference available, but they reflect legal liability, not durability. Terms vary across brands and product types, and longer warranties do not necessarily indicate longer-lasting performance.

Where lifespan estimates are mentioned, they often appear in informal formats, such as FAQ pages or general support materials, rather than in technical documentation [189]. For instance, refrigerator lifespans are cited as 8 to 12 years, but this range is not consistently backed by standardized reporting. Maintenance guidance tends to focus on routine care rather than long-term performance. While some corporate sustainability reports reference repair or circularity goals, few include measurable targets for extending product life.

Third-party research provides a more realistic picture. A *Consumer Reports* study found that 34% of refrigerators required repair within the first five years of ownership, suggesting a disconnect between reported durability and real-world performance [190]. Advocacy groups such as the Consumer Technology Association (CTA) have noted increasing consumer interest in sustainability [191], but also point to persistent repairability barriers, including proprietary components and limited access to spare parts [156], [192].

Meanwhile, major manufacturers continue to centre sustainability messaging around emissions and resource use, while largely avoiding direct commitments to durability. Brands like HP [31] and Whirlpool [29] have issued circularity or net-zero goals, but these typically exclude specific targets for product longevity. Information on take-back programs, repair initiatives, and end-of-life practices is similarly sparse, highlighting a lack of accountability for designing long-lasting products.

Without standardized, product-specific lifespan data, it is difficult to evaluate emissions linked to frequent replacements or track industry progress. The current lack of transparency prevents consumers and regulators from identifying which products are built to last, as well as the real environmental impact of short-lived products. This erodes incentives for durability-focused design, as there is no clear advantage or market signal differentiating longer-lasting products from shorter-lived alternatives.

## 4.2 Overall Recommendations

The recommendations in this report are structured around the three primary impact categories examined in this research. For each, the report identifies clear opportunities for action by standards bodies, regulators, and industry actors. The proposed actions emphasize the need for standardization, data transparency, and whole life-cycle alignment. They also include enabling supporting actions, such as regulatory oversight, strategic data development, and market-driven incentives.

Figure 24 presents the Standards Development Path, a visual summary of the full implementation framework detailed in Appendix E. This figure organizes recommendations by implementation phase and uses colour-coding to show the overlaps and distinctions between the three impact categories. Together, these recommendations form a coordinated road map to align residential equipment standards with Canada's decarbonization goals and to advance circular, durable, and emissions-literate product design.

### 4.2.1 Recommendations to Integrate Embodied Carbon Reporting into Standards

#### Near Term

**Recommendation 1:** Adopt a residential-specific, national whole-building embodied carbon assessment methodology for Canada, like the RESNET/ANSI 1550 approach currently being developed in the U.S. Develop and include Canadian standards for LCA assumptions specific to residential equipment, including refrigerant leakage rates, service life expectations, and end-of-life treatment conditions.

This is a foundational recommendation. Without a residential wbLCA framework, there is no consistent context in which to report or evaluate residential equipment emissions. While the NRC guidelines offer strong guidance for larger commercial buildings, there is no equivalent standard for low-rise residential construction, where emissions reporting is currently fragmented and inconsistent. Without consistent assumptions for refrigerant leakage rates, service life, and end-of-life outcomes, LCAs of residential equipment remain incomplete and difficult to compare. Developing Canadian-specific standards for these key LCA parameters would harmonize data structures, improve the reliability of emissions reporting, and help ensure that reduction strategies target the most impactful life-cycle stages. Developing a coordinated methodology for homes, aligned with existing federal policy and developing U.S.-based standards, and inclusive of MEP systems, would address what many industry experts describe as a "wild west" landscape and enable meaningful emissions comparisons, regulation, and reductions across the residential sector.

**Recommendation 2:** Develop Product Category Rules (PCRs) to support Environmental Product Declaration (EPD) development across residential equipment categories. Require public-sector oversight to help ensure consistency and full market representation and to prevent the emergence of uncoordinated, competing private-sector PCRs.

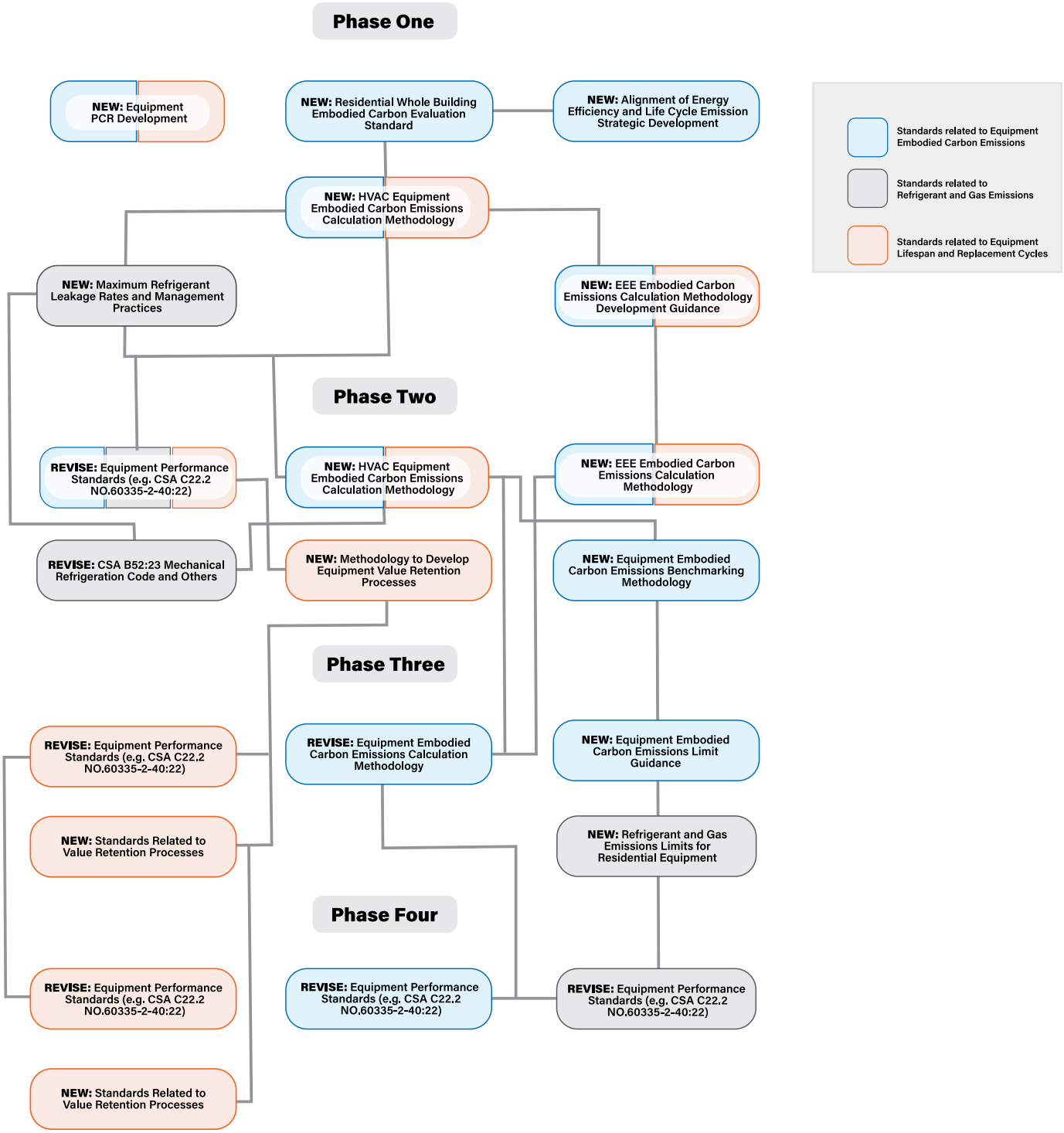
Expanding PCR development by qualified program operators is essential to creating a standardized approach to embodied carbon reporting across residential product categories. EPDs and PEPs enable manufacturers to design products with lower carbon footprints and improved sustainability performance.

**Recommendation 3:** Adopt the TM65NA methodology as a Canadian standard to require and guide residential equipment emissions reporting. Report results into the normative body of equipment performance standards and build a national database of residential equipment embodied carbon assumptions to support wbLCA and reporting requirements in advance of widespread EPD availability.

The lack of standardized data on embodied carbon emissions for residential equipment impedes whole-building carbon assessments and emissions reporting. Adopting TM65NA as a Canadian standard and building a national database of equipment emissions assumptions could bridge critical data gaps, enabling consistent reporting practices ahead of broader EPD availability. This approach enables consistent reporting while full product transparency continues to evolve.

**Figure 24: Standards Development Path**

*This image identifies the relationships between standard develoment recommendations, and identifies the hierarchies and dependencies of those recommendations. Items with multiple colors address multiple impact categories. Note that the time frames of the phases are not specified. For example, items in Phase Two pertaining to one impact category may be achieved prior to beginning Phase Two of another impact category, however the relationships between these items and phases should be coordinated. See Appendix E for full details of all recommendations.*



**Recommendation 4:** Conduct research to identify the most effective regulatory and incentive mechanisms to drive consumer and market demand for product data transparency, with specific attention to the residential sector and residential equipment categories.

Weak market demand for residential EPDs remains a major barrier to advancing embodied carbon transparency. While certification programs such as LEED have helped to drive data development in the commercial sector, similar momentum has not yet materialized for residential equipment. Interviews conducted for this research suggest that builders, developers, and mechanical contractors would support greater product transparency if consistent standards and straightforward compliance pathways were established, and manufacturers emphasized that market demand is a necessary precondition for investing in transparency documentation. Targeted regulatory and incentive programs are needed to create the demand signals necessary for broader adoption of embodied carbon reporting practices. The EU's Construction Product Regulation structure can be referenced as precedent for a regulatory-forward framework.

**Recommendation 5:** Conduct research into the relationship between energy efficiency, low-load building design, and embodied carbon reductions in residential equipment. Expand standards and policies to leverage this relationship for comprehensive emissions reduction strategies.

Coordinating building design, energy modelling, mechanical systems, and installation practices offers a major opportunity to reduce total building emissions. When these strategies are addressed together, they improve system longevity, occupant satisfaction, and environmental performance, including reducing embodied carbon. Although existing standards recognize that low-load buildings can support the adoption of smaller mechanical systems, the additional benefits, such as lower equipment production emissions and reduced refrigerant leakage, remain underutilized. Research has begun to explore the relationship between improved energy efficiency and material carbon impacts [129], but further study is needed to fully understand and apply these connections.

#### Future Phases

**Recommendation 6:** As product transparency improves, develop emissions-based product standards that benchmark embodied carbon levels and set emissions limits, similar to energy efficiency standards. Coordinate these standards to support comprehensive carbon emissions reporting and reduction frameworks.

Improving product transparency is a necessary first step to enable benchmarking and emissions limits for embodied carbon. As data availability expands through resources such as TM65NA, EPDs, and standardized reporting frameworks, experts will be better positioned to develop emissions-based product standards. Setting embodied carbon benchmarks and limits, aligned with total carbon emissions frameworks, is essential to creating a complete and actionable picture of a product's climate impact and enabling comprehensive decarbonization strategies.

**Recommendation 7:** Conduct research to expand TM65NA methodology to include electrical and electronic equipment. Develop alignment strategies between electrical and electronic equipment emissions reporting and wbLCA practices, which currently do not include these product categories.

Current wbLCA practices rarely account for emissions from electrical and electronic equipment, leaving a critical data gap in residential building assessments. Expanding TM65NA to include electrical and electronic equipment and aligning its outputs with the residential wbLCA framework proposed in Recommendation 1, could create a more complete picture of equipment emissions and better support future standards development.

### 4.2.2 Recommendations to Integrate Refrigerant and Gas Emissions into Standards

#### Near Term

**Recommendation 8:** Review existing gas and refrigerant standards to assess their effectiveness in addressing emissions impacts, and update or supplement them as required.

The gap analysis highlights that while Canada maintains strong safety standards for refrigerant- and gas-based systems, these do not explicitly address emissions impacts. Existing frameworks provide a solid foundation, but updates are needed to integrate emissions-focused requirements, especially for residential-scale systems and diverse end-of-life scenarios. In particular, end-of-life refrigerant management must be strengthened wherever possible.

**Recommendation 9:** Adapt international standards such as ASHRAE Standard 196 for refrigerant emissions testing and measurement for use in the Canadian market. Conduct research to develop national standards for refrigerant leakage rate assumptions specific to Canadian contexts (see also Recommendation 1).

Industry leadership provides a strong starting point for advancing refrigerant emissions management. The development of ASHRAE Standard 196 and associated testing facilities demonstrates a proactive approach to establishing verifiable leakage measurement methods. Additional industry-led efforts, including research on low-GWP refrigerants and increased emissions transparency, highlight the value of engaging manufacturers as key partners in shaping practical, enforceable standards. Adapting proven international standards and developing national leakage rate assumptions for the Canadian context will strengthen emissions-focused practices and consistent reporting values for residential systems.

**Recommendation 10:** Recommend regulatory harmonization for the installation and decommissioning of refrigerant-based residential systems to support comprehensive and consistent product installation and refrigerant management requirements.

Mechanical contractors interviewed for this research emphasized the need for clearer guidance, stronger training, and more consistent enforcement. As refrigerant-based technologies continue to grow, regulatory oversight must keep pace to reduce fugitive emissions and improve installation quality. Expanding oversight through improved contractor verification, updated training, and stronger enforcement will help ensure these systems contribute to, rather than hinder, Canada's decarbonization goals. The *Environmental Code of Practice for the Elimination of Fluorocarbon Emissions* provides a strong foundation, but broader adoption and accountability measures are needed to address inconsistent field practices and create fairer industry conditions.

### Future Phases

**Recommendation 11:** Develop standards for residential-scale refrigerant management and require the inclusion of emissions-related information in product documentation.

Refrigerant management intersects with energy performance, system design, and long-term emissions. Standards should address residential-scale refrigerant practices and require emissions-related data in product documentation to support both improved equipment performance and environmental impact outcomes. Aligning product, installation, and building-level metrics will support more consistent emissions tracking and better performance outcomes throughout the equipment life cycle.

**Recommendation 12:** Conduct research and develop standards and regulatory policies to address fugitive gas emissions throughout the gas distribution infrastructure.

While this report focuses on building-level equipment, research findings point to the substantial and often under-reported emissions associated with gas distribution infrastructure. These fugitive emissions, while outside the direct system boundary of this study, are closely tied to the continued use of gas-powered equipment in buildings. Buildings represent the demand side of this infrastructure, making them a critical part of the system's emissions profile. Although some efforts are likely underway to quantify and mitigate these emissions, it is unclear whether existing policies are sufficient or whether they are meaningfully coordinated with building-level decarbonization strategies. Assigning Scope 3 emissions values to buildings that rely on gas could help capture the full impact of this infrastructure, improve emissions accounting, and support more integrated policy development focused on reducing fugitive emissions throughout the gas network.

### 4.2.3 Recommendations to Integrate Equipment Lifespan into Standards

#### Near Term

**Recommendation 13:** Develop Product Category Rules (PCRs) for residential equipment that include standardized reporting of Reference Service Life (RSL) information to support consistent LCA assumptions and align with national standards.

PCR development presents a key opportunity to address lifespan data gaps. Aligning residential equipment PCRs with ISO 15686 would standardize reporting of RSL and embed durability expectations into emissions assessments. This would help support product comparability, incentivize longer-lasting design, and reduce emissions tied to frequent replacements. RSL data could also inform repairability scoring and end-of-life strategies, reinforcing circularity alongside decarbonization goals (see Recommendation 2).

**Recommendation 14:** Conduct research to inform standards development for end-of-life process management, including recycling, disassembly, and material recovery for residential equipment.

End-of-life management is a critical yet underdeveloped opportunity for emissions reduction. Developing standards for recycling, disassembly, and material recovery could minimize landfill waste and reclaim valuable resources. Regulating refrigerant capture during decommissioning is especially urgent, given the widespread release of high-GWP gases at end-of-life (see Recommendation 11). Research is needed to guide standards that shift C-stage practices toward sustainable outcomes and lay the groundwork for future D-stage benefits such as reuse and avoided emissions.

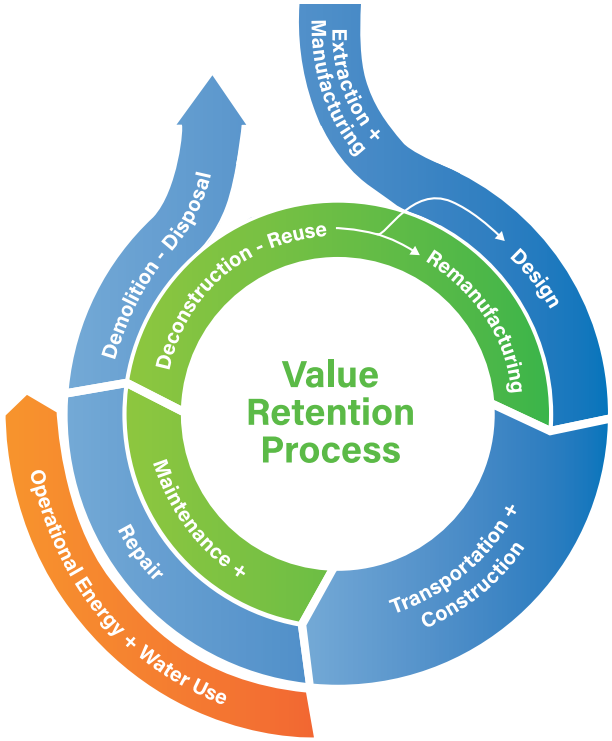
#### Future Phases

**Recommendation 15:** Conduct research and consider development of standards to support Value Retention Processes (VRPs) such as repair, refurbishment, and remanufacturing across residential equipment categories.

Repair, refurbishment, and remanufacturing, collectively known as VRPs, play a central role in extending product life and reducing emissions (see Figure 25). Developing standards to support VRPs could help reduce material demand and replacement frequency, particularly for short-lived or complex equipment. Integrating service life and repairability into performance standards could enable circular and low-carbon outcomes at the product and building scale.

**Figure 25: Value Retention Processes in the Equipment Life Cycle**

*Value Retention Processes (VRPs), including repair, refurbishment, and remanufacturing, extend product life by intervening at key points in the equipment life cycle. Supporting these processes through standards can reduce emissions, limit material demand, and improve the circularity of residential equipment.*




### 4.2.4 Other Recommendations and Next Steps

While this report focuses on the role of standards in reducing emissions from residential equipment, one of the key findings is that standards alone are not enough. Without supportive regulatory frameworks, strong market signals, and coordinated industry engagement, even well-designed standards will struggle to drive meaningful change.

Some of the recommendations above extend beyond traditional standards development to address critical enablers, such as oversight of equipment installation and decommissioning, as well as policies to generate demand for product transparency. These complementary efforts are essential to ensure that standards are adopted, enforced, and effective in real-world contexts.

Moving forward, there is a need to identify and pursue aligned strategies through policy, procurement, capacity building, and education that can accelerate the uptake and implementation of the standards-based recommendations presented here. Doing so will help build the infrastructure for a durable, low-emissions, and circular residential equipment sector in Canada.

## 5 Conclusions

This report lays the groundwork for comprehensively integrating embodied carbon considerations into Canadian standards for residential equipment. While progress has been made in reducing operational emissions, embodied carbon from materials and manufacturing, fugitive refrigerant and gas emissions, and emissions tied to short service lives and frequent replacements remain largely unregulated, despite their growing impact. These overlooked emissions span the full equipment life cycle and must be addressed if Canada is to meet its near- and long-term climate goals.

By evaluating equipment emissions, identifying critical data and methodological gaps, and assessing the alignment of existing standards, this research provides a foundation for more consistent, transparent, and accountable emissions tracking. It offers practical pathways for integrating these concepts into standards, supported by precedent, industry input, and international best practices.

The recommendations in this report are designed not only to inform future Canadian standards, but to help ensure they are implementable. They meet the industry where it is today, by aligning with market signals, regulatory frameworks, and industry capacity. By embedding emissions, durability, and circularity into how residential equipment is regulated and understood, Canada can shift from reaction to leadership.

What is at stake is more than just improved accounting. It is the ability to design equipment and buildings with their full environmental impact in mind. It is the ability to enable informed decision making, reduce waste, reward durability, and bring transparency to a product category that has long been shielded from scrutiny. It is also the opportunity to ensure that Canada's built environment is not only energy efficient but materially intelligent.

In doing so, this work supports a future where durability, transparency, and performance define competitiveness on the global stage and helps position Canada's residential equipment sector to meet the demands of a carbon-conscious future.

# References


[1] United Nations Environment Programme, "Not just another brick in the wall: The solutions exist – Scaling them will build on progress and cut emissions fast. Global Status Report for Buildings and Construction 2024/2025," United Nations Environment Programme, 2025. doi: 10.59117/20.500.11822/47214.

[2] Environment Canada, "Canada's Emissions Trends," Environment Canada, 2014. [Online]. Available: https://publications.gc.ca/collections/collection_2014/ec/En81-18-2014-eng.pdf

[3] M. Lambert, A. Jensen, S. Raju, and M. Lewis, "2025 Embodied Carbon Reductions Built Project Case Study Collection," Carbon Leadership Forum, 2025. [Online]. Available: https://carbonleadershipforum.org/2025-embodied-carbon-reductions-built-project-case-study-collection/

[4] Communications, "New Design Resources for Embodied Carbon Targets – Blog," RDH Building Science. [Online]. Available: https://www.rdh.com/blog/embodied-carbon-resources-for-building-enclosures/

[5] ICLEI, "City Of Vancouver: Zero Emissions Buildings: A Strong Foundation for 100% Renewable Energy and Carbon Neutrality," ICILI, Germany, 2021. [Online]. Available: https://renewablesroadmap.iclei.org/wp-content/uploads/2021/11/Vancouver-case-study_final_compressed-1.pdf

[6] B. X. Rodriguez, M. Huang, H. W. Lee, K. Simonen, and J. Ditto, "Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation," *Energy Build.,* vol. 226, p. 110324, Nov. 2020, doi: 10.1016/j.enbuild.2020.110324.

[7] M. Roberts, C. Ouellet-Plamondon, and P. Raftery, "Embodied carbon in mechanical, electrical, and plumbing systems: A critical literature review," *Build. Environ., vol. 275,* p. 112823, May 2025, doi: 10.1016/j.buildenv.2025.112823.

[8] *Embodied Carbon in Building Services: Residential Heating," Chartered Institution of Building Services Engineers,* CIBSE TM65.1, Chartered Institution of Building Services Engineers, London, United Kingdom, 2021. [Online]. Available: https://www.cibse.org/knowledge-research/knowledge-portal/tm651-embodied-carbon-in-building-services-residential-heating/

[9] Natural Resources Canada, "Government of Canada's New Canada Green Buildings Strategy: A Plan to Help Canadians Save Money on Their Energy Bills," www.canada.ca. https://www.canada.ca/en/natural-resources-canada/news/2024/07/government-of-canadas-new-canada-green-buildings-strategy-a-plan-to-help-canadians-save-money-on-their-energy-bills.html (accessed Nov. 30, 2024).

[10] Government of Canada. *Canadian Net-Zero Emissions Accountability Act.* 2021. [Online]. Available: https://laws-lois.justice.gc.ca/eng/acts/c-19.3/fulltext.html

[11] M. Bowick, J. O'Connor, J. Salazar, J. Meil, and R. Cooney, "National guidelines for whole-building life cycle assessment," 2022. [Online]. Available: https://nrc-publications.canada.ca/eng/view/ft/?id=f7bd265d-cc3d-4848-a666-8eeb1fbde910

[12] Treasury Board of Canada Secretariat, "Standard on the Disclosure of Greenhouse Gas Emissions and the Setting of Reduction Targets," 2022. [Online]. Available: https://www.tbs-sct.canada.ca/pol/doc-eng.aspx?id=32743

[13] *Standard for Calculating and Reporting the Embodied Carbon of Buildings with Dwelling and Sleeping Units,* RESNET C1550 draft, Residential Energy Services Network, 2024. [Online]. Available: https://www.resnet.us/wp-content/uploads/Draft-RESNET-C1550_webcmnt.docx

[14] American Society of Heating, Refrigerating and Air-Conditioning Engineers, "ASHRAE: Service Life and Maintenance Cost Database." Ashrae.org. http://weblegacy.ashrae.org/publicdatabase/service_life.asp (accessed Nov. 30, 2024).

[15] ASHRAE, "Economic Analyses and Life Cycle Costs," 2019. [Online]. Available: https://xp20.ashrae.org/SupplementalFiles/PHVAC9/Economic_Analyses_and_LCC.pdf

[16] California Public Utilities Commission, "A Roadmap for Accelerating the Adoption of Low-Global Warming Potential HVAC Refrigerants," May 2021. [Online]. Available: https://www.calmac.org/publications/CPUC_HVAC_Refrigerants_-_PDS_05032021_FinalReport.pdf

[17] M. Ashtiani, J. Palmeri, and K. Simonen, *End-of-Life Modeling and Data in North American Whole Building Life Cycle Assessment Tools.* Carbon Leadership Forum, University of Washington, Seattle, WA, Apr. 2024. [Online]. Available: https://carbonleadershipforum.org/eol-modeling-data-wblca/

[18] M. Lewis, L. Watkins, C. Loader, and M. Lambert, "Project Life Cycle Assessment Requirements: ECHO Recommendations for Alignment," September 2024. [Online]. Available: https://static1.squarespace.com/static/65302e85ede46f4cf2b0d174/t/67913dfa6a485343747eefc2/1737571837083/Project%2BLCA%2BRequirements%2BECHO%2BRecommendations%2Bfor%2BAlignment_20250117.pdf

[19] "MEP 2040 Refrigerant Impact Calculator." [Online]. Available: https://refrigerant-impact.org/

[20] Greenhouse Gas Protocol. "GHG Protocol: Calculation Tools and Guidance." ghgprotocol.org. https://ghgprotocol.org/calculation-tools-and-guidance (accessed Nov. 30, 2024).

[21] One Click LCA. "The sustainability platform for construction and manufacturing." https://oneclicklca.com/en-us/ (accessed May 6, 2025).

[22] International EPD System, "Search the PCR Library." [Online]. Available: https://environdec.com/pcr-library/with-documents. (accessed Dec. 1, 2024).

[23] EPD International, "EPD Library." [Online]. Available: https://environdec.com/library. (accessed Dec. 1, 2024).

[24] ÖKOBAUDAT. "Sustainable Construction Information Portal. https://www.oekobaudat.de/no_cache/en/database/search.html (accessed Dec. 1, 2024).

[25] Danby Canada. "Product Manuals." danby.com. https://www.danby.com/support/product-manuals/ (accessed May 6, 2025).

[26] GE Appliances. "Life Span of an Appliance." geappliances.com. https://products.geappliances.com/appliance/gea-support-search-content?contentId=21100&_ga=2.217973521.628292171730215716-1459790758.1730215716 (accessed May 6, 2025).

[27] Miele. "Miele G 7656 SCVi AutoDos." miele.ca. https://www.miele.ca/en/Shop/products/detail/fully-integrated-dishwashers-g-7656-scvi-autodos-12497400-p (accessed May 6, 2025).

[28] Whirlpool, "WHIRLPOOL® Laundry Limited Warranty - W10804688-W," [Online]. Available: https://www.whirlpool.com/content/dam/global/documents/201710/Warranty%20Page%20-%20W10804688-W.pdf

[29] Whirlpool, "Whirlpool 2024 Sustainability Report," [Online]. Available: https://sr.whirlpoolcorp.com/

[30] Miele, "Sustainability at Miele." Accessed: May 06, 2025. [Online]. Available: https://www.miele.com/en/c/sustainability-3359.htm

[31] HP. "HP Sustainable Impact – Documents & Reports." hp.com. https://www.hp.com/us-en/sustainable-impact/document-reports.html (accessed May 6, 2025).

[32] GE, "GE 2022 Sustainability Report," [Online]. Available: https://www.ge.com/sites/default/files/ge2022_sustainability_report.pdf

[33] Consumer Reports. "Buy, Own, and Live Better." https://www.consumerreports.org/ (accessed Dec. 5, 2024).

[34] CTA. "The Association for Technology.," https://www.cta.tech/ (accessed Dec. 5, 2024).

[35] Organisation for Economic Co-operation and Development. "Publications." https://www.oecd.org/en/publications/reports.html (accessed May 6, 2025).

[36] United Nations Environmental Programme, "2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector," Nairobi, [Online]. Available: https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction#:~:text=The%20Buildings-GSR%20provides%20an%20annual%20snapshot%20of%20the,sector%20is%20aligned%20with%20the%20Paris%20Agreement%20goals

[37] Builders for Climate Action, "Material Carbon Emissions Estimator (MCE2) MCE² Mechanical, Electrical and Plumbing Dataset Development," NRCan, Feb. 1, 2025. [Online]. Available: https://www.buildersforclimateaction.org/mep-dataset-development.html

[38] B. R. Kyle, S. H. C. Foo, and D. Torrey, "Standards Development Leading to Change in Design and Deconstruction Practices," [Online]. Available: https://www.irbnet.de/daten/iconda/CIB_DC25204.pdf

[39] M. Lewis, M. Huang, S. Carlisle, and K. Simonen, "AIA-CLF Embodied Carbon Toolkit for Architects," Carbon Leadership Forum, Oct. 2021. [Online]. Available: https://carbonleadershipforum.org/clf-architect-toolkit/

[40] World Green Building Council, "Bringing Embodied Carbon Upfront: Coordinated action for the building and construction sector to tackle embodied carbon," 2019. [Online]. Available: https://worldgbc.s3.eu-west-2.amazonaws.com/wp-content/uploads/2022/09/22123951/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf

[41] C. Alejandre, O. Akizu-Gardoki, and E. Lizundia, "Optimum operational lifespan of household appliances considering manufacturing and use stage improvements via life cycle assessment," *Sustain. Prod. Consum.*, vol. 32, pp. 52-65, Jul. 2022, doi: 10.1016/j.spc.2022.04.007.

[42] L. Hamot and C. B. George, *TM65: Embodied carbon in building services: A calculation methodology,* Chartered Institution of Building Services Engineers, London, 2021. [Online]. Available: https://www.cibse.org/knowledge-research/knowledge-portal/embodied-carbon-in-building-services-a-calculation-methodology-tm65

[43] M. Deru and L. Harnot, "TM65NA Embodied carbon in building services: a calculation methodology for North America," Chartered Institution of Building Services Engineers, London, 2024. [Online]. Available: https://www.cibse.org/knowledge-research/knowledge-portal/embodied-carbon-in-building-services-a-calculation-methodology-for-north-america/#:~:text=2024%20ISBN%209781914543913-,Embodied%20carbon%20in%20building%20services%3A%20A%20calculation%20methodology%20for%20North,States%20of%20America%20and%20Mexico%2C

[44] B. X. R. Droguett, "Embodied Carbon of Heating, Ventilation, Air Conditioning and Refrigerants (HVAC+R) Systems," 2019. [Online]. Available: https://digital.lib.washington.edu/server/api/core/bitstreams/c5f6b90a-1bb1-40cf-b9ba-a41e1a3d8b40/content

[45] United Nations, "Paris Agreement," 2015. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[46] United Nations Environment Programme. "Climate action." unep.org. https://www.unep.org/topics/climate-action (accessed May 6, 2025).

[47] Natural Resources Canada. "Keeping the Heat In." canada.ca https://natural-resources.canada.ca/energy-efficiency/home-energy-efficiency/keeping-heat (accessed May 6, 2025).

[48] United Nations, "Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer," 2016. [Online]. Available: https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-f&chapter=27&clang=_en

[49] Justice Canada. "Consolidated federal laws of Canada, Ozone-depleting Substances and Halocarbon Alternatives Regulations." canada.ca https://laws-lois.justice.gc.ca/eng/regulations/SOR-2016-137/FullText.html (accessed Feb. 4, 2025).

[50] Treasury Board of Canada Secretariat. "Standard on Embodied Carbon in Construction." canada.ca https://www.tbs-sct.canada.ca/pol/doc-eng.aspx?id=32814 (accessed Nov. 30, 2024)

[51] CleanBC. "BC is rising to the challenge of climate change." https://cleanbc.gov.bc.ca/ (accessed May 6, 2025).

[52] Buildingexpert.ca. "Ecoperformance program." https://expertbatiment.ca/en/efficiency/programme-ecoperformance/ (accessed May 6, 2025).

[53] Government of British Columbia. "BC Energy and Zero Carbon Step Code." www2.gov.bc.ca https://energystepcode.ca/ (accessed May 6, 2025).

[54] NearZero. "A research program with generous incentives to accelerate the decarbonization of BC homes." https://nearzero.ca/ (accessed May 6, 2025).

[55] Carbon Leadership Forum. "Buy Clean Policies: Overview + Implementation." https://carbonleadershipforum.org/buy-clean-policies-overview/ (accessed May 6, 2025).

[56] Office of the Federal Chief Sustainability Officer. "Federal Buy Clean Initiative." https://www.sustainability.gov/archive/biden46/buyclean/index.html#about (accessed May 6, 2025).

[57] U.S. Department of Energy. "Inflation Reduction Act of 2022." https://www.energy.gov/lpo/inflation-reduction-act-2022 (accessed May 6, 2025).

[58] Library of Congress. "Hands Off Our Home Appliances Act." https://www.congress.gov/bill/118th-congress/house-bill/6192 (accessed May 6, 2025).

[59] Carbon Leadership Forum. "Embodied Carbon Policy Tracking Map." https://batchgeo.com/map/0a7f165939da9d291b183cfc7c326726 (accessed May 6, 2025).

[60] European Commission. "The European Green Deal." https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed May 6, 2025).

[61] Official Journal of the European Union, "Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/ECText with EEA relevance," June 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401781

[62] European Commission. "A quick introduction to Level(s)." https://environment.ec.europa.eu/topics/circular-economy/levels/quick-introduction-levels_en (accessed Feb. 26, 2025).

[63] Ministries of Regional Planning and Ecological Transition. "Environmental regulation RE2020." https://www.ecologie.gouv.fr/politiques-publiques/reglementation-environnementale-re2020(accessed Feb. 26, 2025).

[64] European Commission. "Circular Economy Action Plan." https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (accessed Feb. 26, 2025).

[65] European Commission. "Construction Products Regulation (CPR)." https://single-market-economy.ec.europa.eu/sectors/construction/construction-products-regulation-cpr_en (accessed May 6, 2025).

[66] K. Peterson, C. Balaras, D. Crawley, J. Edelson, R. Hedrick, C. Nesler, E. Tomlinson, and P. Torcellini, "ASHRAE Position Document on Building Decarbonization," 2022. [Online]. Available: https://www.ashrae.org/file%20library/about/position%20documents/pd-on-building-decarbonization-english.pdf

[67] World Green Building Council. "The Net Zero Carbon Buildings Commitment." https://worldgbc.org/thecommitment/ (accessed May 6, 2025).

[68] Canada Green Building Council. "Building our way forward." https://www.cagbc.org/ (accessed May 6, 2025).

[69] Efficiency Canada. "We are the voice for an energy efficient economy." https://www.efficiencycanada.org/ (accessed May 6, 2025).

[70] Canada Green Building Council. "Zero Carbon Building Standards." https://www.cagbc.org/our-work/certification/zero-carbon-building-standard/ (accessed Feb. 26, 2025).

[71] Clean Energy Canada. "Realizing solutions." https://cleanenergycanada.org/ (accessed May 5, 2025).

[72] International Code Council. "The International Code Council and ASHRAE Seek Public Comments on Proposed Standard on Greenhouse Gas Emissions Evaluation." https://www.iccsafe.org/about/periodicals-and-newsroom/the-international-code-council-and-ashrae-seek-public-comments-on-proposed-standard-on-greenhouse-gas-emissions-evaluation/ (accessed May 6, 2025).

[73] *Embodied carbon in building services: A calculation methodology (2021),* Chartered Institution of Building Services Engineers, London, United Kingdom, 2014. [Online]. Available: https://www.cibse.org/knowledge-research/knowledge-portal/embodied-carbon-in-building-services-a-calculation-methodology-tm65

[74] Carbon Leadership Forum. "Join us in decarbonizing the built environment." https://carbonleadershipforum.org/ (accessed May 6, 2025).

[75] Building Transparency. "Our Tools." https://www.buildingtransparency.org/tools/ (accessed Nov. 30, 2024).

[76] PACT: Partnership for Carbon Transparency. "Accelerating global value chain transparency. Together." https://www.carbon-transparency.org/ (accessed Jan. 2, 2025).

[77] ECHO Project. "Project Life Cycle Assessment Requirements – ECHO Recommendations for Alignment (October 2024)." https://www.echo-project.info (accessed May 6, 2025).

[78] Living Future Institute. "Zero Carbon Certification." https://living-future.org/zero-carbon/ (accessed Feb. 26, 2025).

[79] SE2050. "Committing to Net Zero." https://se2050.org/ (accessed Feb. 26, 2025).

[80] MEP 2040. "Download the beginner's guide to MEP embodied carbon." https://www.mep2040.org/ (accessed Feb. 26, 2025).

[81] Building Transparency. "Everyone Can Help Decarbonize Buildings." https://www.buildingtransparency.org/programs/carbon-action-network/ (accessed Feb. 26, 2025).

[82] RMI. "HomebuildersCAN." https://rmi.org/homebuilderscan/ (accessed Feb. 26, 2025).

[83] Architecture 20230. "The 2030 Challenge." https://www.architecture2030.org/2030_challenges/2030-challenge/ (accessed Feb. 26, 2025).

[84] AIA. "The AIA 2030 Commitment." https://www.aia.org/design-excellence/climate-action/zero-carbon/2030-commitment (accessed Feb. 26, 2025).

[85] ENERGY STAR. "The simple choice for saving energy." https://www.energystar.gov/ (accessed Feb. 26, 2025).

[86] Natural Resources Canada. "EnerGuide in Canada." https://natural-resources.canada.ca/energy-efficiency/product-energy-ratings/energuide (accessed Feb. 26, 2025).

[87] BC Hydro. "Residential rebates and free programs." https://www.bchydro.com/powersmart/residential/rebates-programs.html (accessed Feb. 26, 2025).

[88] Save on Energy. "Discover your energy-saving potential." https://www.saveonenergy.ca/ (accessed Feb. 26, 2025).

[89] United States Environmental Protection Agency. "Labeling of Construction Materials & Products." https://www.epa.gov/greenerproducts/labeling-materials-products (accessed Feb. 26, 2025).

[90] H. Elwood and T. Brooks, "Draft Approach for Stakeholder Input: Implementation of the EPA Label Program for Low Embodied Carbon Construction Materials," Feb. 27, 2024. [Online]. Available: https://www.epa.gov/system/files/documents/2024-03/epa-hq-oppt-2024-0038-0002_content.pdf

[91] U.S. Green Building Council. "LEED v5 early adopters." https://www.usgbc.org/leed/v5 (accessed Feb. 26, 2025).

[92] Living Future. "The Declare Label." https://living-future.org/declare/ (accessed Feb. 26, 2025).

[93] mindful MATERIALS. "Our Work." https://www.mindfulmaterials.com (accessed Nov. 30, 2024).

[94] Ellen MacArthur Foundation. "It's Time for a Circular Economy." https://www.ellenmacarthurfoundation.org/ (accessed May 6, 2025).

[95] Cradle to Cradle Products Innovation Institute. "Product circularity, verified." https://c2ccertified.org/ (accessed Nov. 30, 2024).

[96] European Commission. "EU Ecolabel." https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel_en (accessed May 6, 2025).

[97] Charles Mougeot, "Community Technology Assessment Platform (CTAP)," CANMET Energy, NRCan, Ottawa, Ontario, Canada, Mar. 2024. Accessed: Jul. 07, 2025. [Online]. Available: https://natural-resources.canada.ca/sites/nrcan/files/canmetenergy/pdf/CTAP%20User%20Guide%20EN.pdf

[98] J. O'Brien and H. Stoch, "ESG: Getting serious about decarbonisation: From Strategy to execution," Deloitte, 2021. [Online]. Available: https://www.deloitte.com/au/en/Industries/power-utilities-renewables/perspectives/getting-serious-decarbonisation-strategy-execution.html

[99] N. Nasr, J. Russell, S. Bringezu, S. Hellweg, B. Hilton, C. Kreiss, and N. von Gries, "Re-defining Value – The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy.," IRP, United Nations Environment Programme, Nairobi, Kenya, 2018. [Online]. Available: https://www.resourcepanel.org/reports/re-defining-value-manufacturing-revolution

[100] Environment and Climate Change Canada, "Economic Study of the Canadian Plastic Industry, Market and Waste," 2019. [Online]. Available: https://publications.gc.ca/collections/collection_2019/eccc/En4-366-1-2019-eng.pdf

[101] O. Hollins and Dillon, "Socio-Economic and Environmental Study of the Canadian Remanufacturing Sector and Other Value-Retention Processes (VRPs) in the Context of a Circular Economy," Environment and Climate Change Canada, March 2021. Accessed: Nov. 14, 2024. [Online]. Available: https://publications.gc.ca/collections/collection_2021/eccc/En4-438-2021-eng.pdf

[102] Whirlpool. "Sustainable Use, Scope 3 Emissions." https://sr.whirlpoolcorp.com/our-products/sustainable-use.php (accessed May 6, 2025).

[103] Daikin. "Energy Efficiency Grant." https://www.daikin.com.sg/blog-post/refrigerant-recovery (accessed Feb. 26, 2025).

[104] Daikin Comfort Technologies North America Inc, "Refrigerant Reclamation," [Online]. Available: https://backend.daikincomfort.com/docs/default-source/default-document-library/general/rr-flyer.pdf

[105] World Steel Association. "Circular Economy." https://worldsteel.org/wider-sustainability/circular-economy/ (accessed May 6, 2025).

[106] European Commission, "Annex to the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions," Brussels, Dec. 2015. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_2&format=PDF

[107] European Parliament, Council of the European Union, "Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)," July 4, 2012. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02012L0019-20180704

[108] J. Huisman, F. Magalini, R. Kuehr, and C. Maurer, "2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE)," Jan. 2008.

[109] J. St. Godard and S. Lavalley, "Landscape Review of Repairability in Canada," Canadian Standards Association, Toronto, ON, 2022. [Online]. Available: https://www.csagroup.org/article/research/landscape-review-of-repairability-in-canada/?srsltid=AfmBOoqczmafdDRu85uq8zDh2vbBbeloe53tvDIhhNkmPsiLQHKNOIdW

[110] Z. Teshnizi, M. Wesley, J. Ahmad, K. Kauth, A. Komisar, and R. Zizzo, "Exploring Circular Strategies to Extend the Life of Existing Buildings. Retrofit Versus Demolition and New Construction," Canadian Standards Association, Toronto, ON, 2023. [Online]. Available: https://www.csagroup.org/article/research/exploring-circular-strategies-to-extend-the-life-of-existing-buildings/

[111] H. Goodland and K. Walsh, "Opportunities to Apply Circular Strategies to Existing Office Buildings," Canadian Standards Association, Toronto, ON, 2023. [Online]. Available: https://www.csagroup.org/article/research/opportunities-to-apply-circular-strategies-to-existing-office-buildings

[112] B. Rodriguez, L. Amany, and K. Simonen, "'Embodied and Operational Carbon of Typical Heating, Ventilation and Air Conditioning (HVAC) Systems in Office Buildings in Washington State: A study of buildings registered under LEED v3 2009,'" *IOP Conf. Ser. Earth Environ. Sci.*, vol. 294, no. 1, p. 012057, Jul. 2019, doi: 10.1088/1755-1315/294/1/012057.

[113] G. Annan, "Unlocking Sustainability in Building Systems: A Guide to Whole Life Carbon for MEP Systems," ASHRAE. [Online]. Available: https://www.ashrae.org/news/esociety/unlocking-sustainability-in-building-systems-a-guide-to-whole-life-carbon-for-mep-systems

[114] Natural Resources Canada, "Powering Canada's Future: A Clean Electricity Strategy." [Online]. Available: https://natural-resources.canada.ca/our-natural-resources/energy-sources-distribution/electricity-infrastructure/powering-canadas-future-clean-electricity-strategy/26533

[115] London Energy Transformation Initiative, "LETI Embodied Carbon Primer," Jan. 2020. [Online]. Available: https://www.leti.uk/_files/ugd/252d09_8ceffcbcafdb43cf8a19ab9af5073b92.pdf

[116] R. D. Huulgaard, R. Dalgaard, and S. Merciai, "Ecodesign requirements for televisions—is energy consumption in the use phase the only relevant requirement?," *Int. J. Life Cycle Assess.,* vol. 18, no. 5, pp. 1098-1105, Jun. 2013, doi: 10.1007/s11367-013-0554-8.

[117] J. Litardo, D. Gomez, A. Boero, R. Hidalgo-Leon, G. Soriano, and A. D. Ramirez, "Air-conditioning life cycle assessment research: A review of the methodology, environmental impacts, and areas of future improvement," *Energy Build.,* vol. 296, p. 113415, Oct. 2023, doi: 10.1016/j.enbuild.2023.113415.

[118] L. Z. Gergely, E. Barna, M. Horváth, and Z. Szalay, "Assessing embodied and operational carbon of residential HVAC systems: Baselines for life-cycle sustainability," *Build. Environ.,* vol. 269, p. 112442, Feb. 2025, doi: 10.1016/j.buildenv.2024.112442.

[119] W. Wild, J. Lau, and M. Allwood, "The time-value of carbon: An introductory exploration to support better decision making," ARUP, 3, Sep. 2024. [Online]. Available: https://www.arup.com/globalassets/downloads/insights/t/the-time-value-of-carbon/the-time-value-of-carbon-issue-3.pdf

[120] D. Thylmann and R. Kieber, "Biogenic Carbon Guideline on the Consideration of Biogenic Carbon Emissions and Removals in Carbon Footprint Calculations," Textile Exchange, Oct. 2024. [Online]. Available: https://textileexchange.org/app/uploads/2024/11/Biogenic-Carbon-Guideline.pdf

[121] E. Hoxha *et al.,* "Biogenic carbon in buildings: a critical overview of LCA methods," *Build. Cities,* vol. 1, no. 1, pp. 504-524, Aug. 2020, doi: 10.5334/bc.46.

[122] K. Calvin *et al.,* "IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland," Intergovernmental Panel on Climate Change (IPCC), July 2023. doi: 10.59327/IPCC/AR6-9789291691647.

[123] *2011 Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method,* CEN-EN 5978, European Committee for Standardization, Nov. 2011.

[124] United States Environmental Protection Agency. "Scope 1 and Scope 2 Inventory Guidance." https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance (accessed Feb. 26, 2025).

[125] United States Environmental Protection Agency. "Scope 3 Inventory Guidance." https://www.epa.gov/climateleadership/scope-3-inventory-guidance (accessed Feb. 26, 2025).

[126] World Green Building Council. "Bringing Embodied Carbon Upfront." https://worldgbc.org/article/bringing-embodied-carbon-upfront/ (accessed July 7, 2025).

[127] Global Electronics Council, "State of Sustainability Research: Climate Change Mitigation," USA, May 2021. [Online]. Available: https://globalelectronicscouncil.org/wp-content/uploads/GEC_Climate_Change_SOSR_Rev-1_-October-2021-.pdf

[128] C. Magwood, T. Huynh, and V. Olgyay, "The Hidden Climate Impact of Residential Construction," RMI, 2023. [Online]. Available: https://rmi.org/insight/hidden-climate-impact-of-residential-construction/

[129] O. Mayorga Pérez and N. Yalavarthy, Sustainability Review of the Mobile Cooling and Climate Control Industry: A Case Study Incorporating LCA and Materiality Assessment. KTH Royal Institute of Technology, School of Architecture and the Built Environment, Stockholm, Sweden, 2020.

[130] *Sustainability standard for household portable and floor care appliances,* CSA SPE-7002-14, Canadian Standards Association, Toronto, ON, Canada, 2014.

[131] *Sustainability standard for household clothes washers,* CSA R7003:16 (R2021), Canadian Standards Association, Toronto, ON, Canada, 2016.

[132] *Sustainability standard for household cooking appliances,* CSA R7004:17 (R2022), Canadian Standards Association, Toronto, Ontario, Canada., 2017.

[133] *Sustainability standard for household refrigeration appliances,* CSA R7001:21, Canadian Standards Association, Toronto, ON, Canada, Oct. 2021.

[134] *Embodied carbon in building services: A calculation methodology (2021),* TM65, Chartered Institution of Building Services Engineers, London, United Kingdom, 2021.

[135] R. Hischier, F. Reale, V. Castellani, and S. Sala, "Environmental impacts of household appliances in Europe and scenarios for their impact reduction," *J. Clean. Prod.,* vol. 267, p. 121952, Sep. 2020, doi: 10.1016/j.jclepro.2020.121952.

[136] LG Electronics, Environmental Product Declaration: Objet Collection Refrigerator (MF-B6*, F62B, M62**2(S)), NEPD-3952-2990-EN, The Norwegian EPD Foundation, Nov. 28, 2022.

[137] A. Gallego-Schmid, J. M. F. Mendoza, and A. Azapagic, "Environmental assessment of microwaves and the effect of European energy efficiency and waste management legislation," *Sci. Total Environ.,* vol. 618, pp. 487-499, Mar. 2018, doi: 10.1016/j.scitotenv.2017.11.064.

[138] Project Drawdown. "Refrigerant Management." https://drawdown.org/solutions/refrigerant-management (accessed Feb. 26, 2025).

[139] Environment and Climate Change Canada, "Environmental code of practice for the elimination of fluorocarbon emissions from refrigeration and air conditioning systems," April 2015, Errata June 2021. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/publications/code-practice-elimination-fluorocarbon-emissions.html

[140] United States Environmental Protection Agency. "Frequent Questions on the Phasedown of Hydrofluorocarbons." https://www.epa.gov/climate-hfcs-reduction/frequent-questions-phasedown-hydrofluorocarbons (accessed May 12, 2025).

[141] United States Environmental Protection Agency. "Control of HFC-23 Emissions." https://www.epa.gov/climate-hfcs-reduction/control-hfc-23-emissions (accessed Feb. 24, 2025)

[142] European Chemical Industry Council. "A review of current understanding of HFC-23 emissions and contributing source processes." https://www.fluorocarbons.org/news/a-review-of-current-understanding-of-hfc-23-emissions-and-contributing-source-processes/ (accessed Feb. 24, 2025).

[143] B. Adam *et al.,* "Emissions of HFC-23 do not reflect commitments made under the Kigali Amendment," *Commun. Earth Environ.,* vol. 5, no. 1, p. 783, Dec. 2024, doi: 10.1038/s43247-024-01946-y.

[144] Messer Canada Inc, "Refrigerant R290 U.L. Classified Propane," Jan. 2021. [Online]. Available: https://www.hrai.ca/uploads/userfiles/files/R290%20Propane%20GR2_5%20UL%20F.pdf

[145] Trane Technologies, HVAC Industry Update. REFR-PRB001G-EN, Sept. 16, 2021. [Online]. Available: https://www.trane.com/content/dam/Trane/Commercial/global/newsroom/blogs/Documents%202018/HVAC%20Industry%20Update.pdf (accessed Dec. 1, 2024)

[146] A. Penner, "The Changing Landscape of Refrigerants: Knowing the Facts," Association of Energy Engineers, Canada East." [Online]. Available: https://aeecanadaeast.org/2022/03/11/the-changing-landscape-of-refrigerants-knowing-the-facts/

[147] University of Kansas. "Environmentally Applied Refrigerant Technology Hub (EARTH)." https://erc-earth.ku.edu/homepage (accessed May 8, 2025).

[148] US EPA, "Direct Fugitive Emissions from Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gases," 2014. Accessed: May 08, 2025. [Online]. Available: https://www.epa.gov/sites/default/files/2015-07documents/fugitiveemissions.pdf

[149] Redwood Energy, "Zero Emissions All-Electric Multifamily Construction Guide," 2019. [Online]. Available: https://www.redwoodenergy.net/research/a-zero-emissions-all-electric-multifamily-construction-guide

[150] One Click LCA. "Decarbonize MEP Systems." https://oneclicklca.com/en-us/software/design-construction/mep-wholelife-carbon (accessed Feb. 28, 2025).

[151] C. P. Baldé, F. Wang, R. Kuehr, and J. Huisman, "The Global E-waste Monitor 2014: Quantities, flows, and resources," United Nations University, Institute for the Advanced Study on Sustainability, Bonn, 2015. [Online]. Available: https://i.unu.edu/media/unu.edu/news/52624/UNU-1stGlobal-E-Waste-Monitor-2014-small.pdf

[152] Consumer Technology Association, "2022 Technology Product Lifecycle Study," 2022. [Online]. Available: https://shop.cta.tech/products/2022-technology-product-lifecycle-study

[153] A. Dindarian and A. A. P. Gibson, "Reuse of EEE/WEEE in UK: Review on functionality of EEE/WEEE at the point of disposal," in *Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology,* May 2011, pp. 1-5. [Online]. Available: https://ieeexplore.ieee.org/document/5936867

[154] Natural gas and propane installation code, CSA B149. 1:20, Canadian Standards Association, Toronto, ON, Canada, 2021.

[155] EPD International AB, Instant Boiling and Chilled Drinking Water Dispensers (Permanently Installed): Sub-PCR to PCR 2012:01 Construction Products and Construction Services, PCR 2012:01-Sub-PCR-J, The International EPD® System, Nov. 8, 2021.

[156] EPD International AB, Air-Conditioning Machines: Product Category Rules (PCR), PCR 2021:02, Version 1.0.1, The International EPD® System, Apr. 28, 2023.

[157] Chartered Institution of Building Services Engineers, "Guide M: Maintenance Engineering and Management," London, United Kingdom, 2014. [Online]. Available: https://www.cibse.org/knowledge-research/knowledge-portal/guide-m-maintenance-engineering-and-management-2023

[158] *Product category rules for life cycle assessments of electronic and electrical products and systems,* BSI EN 50693:2019, British Standards Institution, 2019.

[159] K. Schischke, M. Proske, N. F. Nissen, and K.-D. Lang, "Modular products: Smartphone design from a circular economy perspective," in *2016 Electronics Goes Green 2016+ (EGG),* Berlin: IEEE, Sep. 2016, pp. 1-8. doi: 10.1109/EGG.2016.7829810.

[160] *Best practices for defueling, decommissioning, and disposal of compressed natural gas vehicle fuel containers and liquefied natural gas vehicle fuel tanks,* CSA SPE-2.1 Series 18, Canadian Standards Association, Toronto, ON, Canada, 2018.

[161] *General requirements — Canadian Electrical Code, Part II,* 2020, CSA C22.2 NO. 0.20, Canadian Standards Association, Toronto, ON, Canada, 2020.

[162] *Canadian Electrical Code, Part I (26th Edition), Safety Standard for Electrical Installations,* CSA C22.1:24, Canadian Standards Association, Toronto, ON< Canada, 2024.

[163] *Performance of electric storage tank water heaters for domestic hot water service,* CAN-CSA-C191-13 (R2022), Canadian Standards Association, Toronto, ON, Canada, 2013.

[164] *Energy performance and capacity of household refrigerators, refrigerator-freezers, freezers, and wine chillers,* CAN/CSA C300-15, Canadian Standards Association, Toronto, ON, Canada, 2015.

[165] *Energy performance and drum volume of household electric clothes dryers,* CAN/CSA-361-16, Canadian Standards Association, Toronto, ON, Canada, 2016.

[166] *Energy performance of drinking water coolers,* CAN-CSA-C815-09 (R2024), Canadian Standards Association, Toronto, ON, Canada, 2009.

[167] Government of Canada. "Energy Efficiency Regulations, 2016." https://laws-lois.justice.gc.ca/eng/regulations/SOR-2016-311/index.html (accessed Mar. 1, 2025)

[168] *Mechanical Refrigeration Code,* CSA B52:23, Canadian Standards Association, Toronto, ON, Canada, 2025. Jul. 2024.

[169] *Refrigeration equipment,* CSA C22.2 No. 120:13 (R2023), Canadian Standards Association, Toronto, ON, Canada, 2013.

[170] *Gas water heaters, volume I, storage water heaters with input ratings of 75,000 Btu per hour or less,* CSA/ANSI Z21.10.1:19 (R2024)/CSA 4.1:19 (R2024), Canadian Standards Association, Toronto, ON, Canada, 2019.

[171] *Connectors for gas appliances,* CSA/ANSI Z21.24:22/CSA 6.10:22, Canadian Standards Association, Toronto, ON, Canada, 2022.

[172] *Gas clothes dryers, volume I, type 1 clothes dryers,* CSA/ANSI Z21.5.1:22/CSA 7.1:22, Canadian Standards Association, Toronto, ON, Canada, 2022.

[173] *Service Regulators for Natural Gas,* CSA 6.18-02 (R2022), Canadian Standards Association, Toronto, ON, Canada, 2002.

[174] *Automatic Gas Shutoff Devices For Hot Water Supply Systems,* ANSI Z21.87-2007 (R2021)/CSA 4.6-2007 (R2021), Canadian Standards Association, Toronto, ON, Canada, 2007.

[175] *Durability in Buildings,* CSA S478:19, Canadian Standards Association, Toronto, ON, Canada, 2019.

[176] *Guideline for Design for Disassembly and Adaptability in Buildings,* Z782-06, Canadian Standards Association, Toronto, ON, Canada, 2006.

[177] *Environmental management — Life cycle assessment — Principles and framework,* ISO 14040:2006, International Organization for Standardization, Geneva, Switzerland, 2006.

[178] *Environmental management — Life cycle assessment — Requirements and guidelines,* ISO 14044:2006, International Organization for Standardization, Geneva, Switzerland, 2006.

[179] *Environmental labels and declarations — Type III environmental declarations — Principles and procedures,* ISO 14025:2006, International Organization for Standardization, Geneva, Switzerland, 2006.

[180] *Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification,* ISO 14067:2018, International Organization for Standardization, Geneva, Switzerland, 2018.

[181] *Buildings and constructed assets — Service life planning Part 1: General principles and framework,* ISO 15686-1:2011, International Organization for Standardization, Geneva, Switzerland, 2011.

[182] Office of the Secretary of State, Vermont, "Vermont Residential Building Energy Standards (RBES) Amendments," 2023. [Online]. Available: https://publicservice.vermont.gov/sites/dps/files/documents/06.21.23%20-%2022P28%20-%20PSD%20Adopted%20Rule%20Filing%20-%20Residential%20Building%20Energy%20Standards.pdf

[183] Government of Massachusetts, "MA 2023 Residential Stretch code and Specialized Opt-in code." [Online]. Available: https://www.mass.gov/doc/225-cmr-22-ma-residential-public-comment-redline-8-8-24/download

[184] *Safety Standard for Refrigeration Systems and Designation and Safety Classification of Refrigerants,* ASHRAE Standard 34-2024, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Georgia, U.S., 2024.

[185] *Safety Standard for Refrigeration Systems in Residential Applications,* ASHRAE Standard 15.2-2022, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Georgia, U.S., 2024.

[186] European Parliament and Council of the European Union, *Directive 2002/95/EC ... on the restriction of the use of certain hazardous substances in electrical and electronic equipment,* Off. J. Eur. Union, L 37/19, Feb. 13, 2003. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2002/95/oj/eng

[187] SGS, "Midea Receives First Life Cycle Assessment (LCA) Certificate for Washing Machines," [Online]. Available: https://www.sgs.com/en/news/2023/10/midea-receives-first-life-cycle-assessment-lca-certificate-for-washing-machines

[188] Heating, Refrigeration and Air Conditioning Institute of Canada, "Refrigerant Management Canada." [Online]. Available: https://www.hrai.ca/refrigerant-management-canada

[189] Danby Canada, "Frequently Asked Questions," [Online]. Available: https://www.danby.com/faqs/

[190] D. Wroclawski, "Most and Least Reliable Refrigerator Brands," Consumer Reports. [Online]. Available: https://www.consumerreports.org/appliances/refrigerators/most-and-least-reliable-refrigerator-brands-a8271265835/

[191] Consumer Technology Association, "Consumer Technology Recycling and Reuse Study 2023." [Online]. Available: https://shop.cta.tech/products/consumer-technology-recycling-and-reuse-study-2023

[192] Consumer Technology Association, "Driving Retail Sustainability with Technology," Oct. 2023. [Online]. Available: https://shop.cta.tech/products/driving-retail-sustainability-with-technology

# Appendix A – Equipment in Scope

| Category | Equipment | Key Attributes | Notes |
|---|---|---|---|
| **Water Heating** | Electric Storage Water Tanks | Emission-intensive manufacturing processes | Frequent replacements due to wear and tear |
| | Gas Storage Water Tanks | Combustion-related emissions (operational and embodied) | Both production emissions and fugitive gas emissions are a risk |
| | Glass Line Storage Water Tanks | Emission-intensive manufacturing processes | Typically associated with other HVAC systems |
| **Appliances** | Refrigerators (Standard full-size residential units (≤1100 L capacity)) | High reliance on refrigerants with high-GWP | Risk of both production emissions and end-of-life fugitive refrigerant emissions |
| | Freezers (Chest or upright freezers (≤850 L capacity)) | Similar emissions profile as refrigerators | Focus on refrigerants and production emissions |
| | Wine Chillers (Refrigerated units for wine storage (≤1100 L capacity)) | Similar emissions profile as refrigerators, reduced by scale | Focus on refrigerants and production emissions |
| | Dishwashers | Energy and water consumption alongside material emissions | Frequent replacements and production emission risks |
| | Electric Ranges | Includes induction and resistance models. | Primarily production emission risks |
| | Clothes Washers (Washer-dryer combos excluded) | Significant emissions from manufacturing and water efficiency | Frequent replacements and production emission risks |
| | Microwaves (Includes countertop and over-the-range models. Defined by voltage and connection type (120/240V)) | Short lifespan with emission-intensive components | Electronics-heavy; contributes significantly to end-of-life impacts; frequent replacements and production emission risks |
| | Televisions (Residential televisions (≥75 cm diagonal screens)) | High embodied emissions due to electronic components | Frequent replacements and production emission risks |
| | Displays (Smaller screens (<75 cm diagonal)) | Emissions profile similar to televisions | Frequent replacements and production emission risks |

| Category | Equipment | Key Attributes | Notes |
|---|---|---|---|
| **HVAC Systems** | Heat Pumps | Includes heat pumps for water heating and space heating and cooling | High reliance on refrigerants and emission-intensive manufacturing |
| | Energy Recovery Ventilators/ Heat Recovery Ventilators | Advanced ventilation systems | Primarily production emission risks |
| | Room Air Conditioners (Defined as portable or fixed units with external venting) | High reliance on refrigerants and frequent replacements | Embodied and refrigerant emissions amplified by shorter lifespans |
| | Portable Air Conditioners (Similar to room air conditioners; defined by mobility.) | Similar considerations as room air conditioners | Often consumer-purchased but included for emission visibility |
| | Dehumidifiers | High material intensity for compact systems | Embodied and refrigerant emissions amplified by shorter lifespans |
| | Humidifiers | Similar to dehumidifiers | Primarily production emission risks and shorter lifespans |
| **Electronics** | Set-top Boxes (Digital TV boxes, including hybrid devices for multiple media types) | Compact electronics with high material intensity | Short lifespans amplify emissions |
| | Battery Charging Systems (Plug-in battery chargers for residential devices (AAA, AA, 12V)) | Includes EV/home chargers | High embodied carbon due to battery manufacturing and electronics |
| | AC-DC & AC-AC Power Supply | Power supplies converting line voltage to low-voltage AC/DC | Limited scope for residential impact compared to larger systems |
| | Small Network Equipment (Defined by criteria such as ≤11 wired network ports and operation outside standard racks) | Routers, modems, and switches with wireless capability | Often overlooked in emissions reporting; high consumption and short lifespans amplify emissions |
| | Line Voltage Thermostats (Includes smart thermostats with advanced controls) | Controls HVAC systems, with electronic components | Often overlooked in emissions reporting; high consumption and short lifespans amplify emissions |

# Appendix B – Additional Screened Standards, Tools, and References

## Durability / Service Life / Performance

- CSA S478: Durability in Buildings
- ISO 15686: Service Life Planning
- VDI 2067: Economic Efficiency of Building Systems
- RICS BCIS Life Expectancy of Building Components
- Fannie Mae: Estimated Useful Life Tables
- InterNACHI (International Association of Certified Home Inspectors)
- IEC 60068: Environmental Testing
- IEC 62368-1: Safety for ICT and AV Equipment
- CIBSE Guide M

## Refrigerants / Mechanical Systems Safety

- CSA B52:23: Mechanical Refrigeration Code
- CSA B52HB:20: Practical Handbook for CSA B52:18
- CSA C22.2 No. 140.3:15: Refrigerant-containing Components
- CSA C22.2 No. 60335-2-89:21: Refrigerating Appliances Safety
- CSA C22.2 No. 63-93: Household Refrigerators and Freezers
- ISO 5149: Refrigeration Systems – Safety and Environmental Requirements
- ISO 14903: Qualification of Tightness of Components and Joints
- ASHRAE 15: Safety Standard for Refrigeration Systems
- ASHRAE 34: Refrigerant Classification
- EN 378: Refrigerant Environmental and Safety Guidelines
- ANSI Z21.87-2007 / CSA 4.6-2007: Automatic Gas Shutoff Devices

## Gas Safety / Installation Codes

- CSA B149.1:20: Natural Gas and Propane Installation Code
- CSA/ANSI Z21.10.1:19 / CSA 4.1:19: Gas Water Heaters
- CSA/ANSI Z21.24:22 / CSA 6.10:22: Connectors for Gas Appliances
- CSA/ANSI Z21.5.1:22 / CSA 7.1:22: Gas Clothes Dryers
- CSA/ANSI Z23550:22: Safety and Control Devices for Burners
- CSA 6.18-02: Service Regulators
- CSA/ANSI Z21.20:22 / CSA C22.2 No. 60730-2-5:22: Burner Control Systems

## Electrical Equipment / Energy Performance

- CSA C22.2 Series: Canadian Electrical Code, Part II
- CSA C22.2 No. 0-10: General Requirements
- CSA C22.2 No. 107.1:16: Power Conversion Equipment
- CSA C300-15: Energy Performance of Electrical Equipment
- CSA C361-12: Performance of Distribution Transformers
- CSA C815-09: Energy Efficiency for Gas Furnaces
- IEC 60335: Safety of Household Electrical Appliances
- ANSI/AHRI 210/240: Air Conditioner and Heat Pump Rating

## Environmental Claims / Management / GHG Accounting

- ISO 14025: Type III Environmental Declarations
- ISO 14040 / 14044: Life Cycle Assessment Principles and Guidelines
- ISO 14067: Carbon Footprint of Products
- CSA ISO 14021:00 / PLUS 14021: Environmental Claims
- CSA ISO 14064-1/2/3: GHG Emissions Quantification and Verification
- CAN/CSA-ISO 14031-00: Environmental Performance Evaluation
- SPE-14040-14: LCA Guidelines for Auto Parts

## Procurement and Circularity

- Z766-95: Environmentally Responsible Procurement
- SPE-2.1 Series-18: Defueling and Disposal of Vehicle Fuel Tanks

## Databases and Digital Tools

- OneClick LCA
- Cerclos eTool
- Building Transparency's EC3
- SmartEPD
- Sustainable Minds Transparency Catalog
- UL SPOT Database
- IPCC Global Warming Potential Database
- PEP Ecopassport Program
- City of Seattle Refrigerant Leakage Study

## Manufacturer Documentation and Product Resources

- Whirlpool Warranty
- Whirlpool Dryer User Manual
- Miele Dishwasher Guide
- Danby Product Manuals
- GE Appliance SEER Inverter Heat Pump Guide
- GE: How to Determine Appliance Manufacture Date
- GE: Appliance Life Span Estimator
- GO ENERGY STAR Washing Machine Guide
- HP Monitor User Guide
- HP Planet Partners: Circular Economy Program
- HP Support Community
- Responsible Appliance Disposal (RAD) Program

## Policy, Guidance, and Voluntary Frameworks

- Standard on the Disclosure of Greenhouse Gas Emissions and the Setting of Reduction Targets (Canada)
- Climate Change Adaptation for Natural Gas and Propane Installations
- GHG Protocol
- Level(s): EU Framework for Sustainable Buildings
- Regulation (EU) 2017/1369: Energy Labelling of Energy-Related Products
- RICS (Royal Institution of Chartered Surveyors)
- CIBSE TM65 / TM65NA

# Appendix C – Interview Participants and Questions

| Stakeholder Category | Questions |
|---|---|
| **Manufacturers** | 1. Would using the simplified ASHRAE TM65NA method be an acceptable interim step for embodied carbon reporting until full EPDs are available? Would a material breakdown and mass disclosure be sufficient?<br>2. What is the current plan or timeline for improving embodied carbon data availability and publishing EPDs for residential equipment?<br>3. Does refrigerant leakage occur during manufacturing? If so, what is the typical scale, why does it happen, and how could management practices improve?<br>4. What are the risks and opportunities for manufacturers in developing and reporting expected equipment life spans?<br>5. Is refurbishment, repair, and reuse (Value Retention Processes) a viable strategy for manufacturers? What challenges or liabilities do VRPs present, and where are the opportunities?<br>6. What are the main challenges and opportunities for manufacturers in supporting end-of-life management, such as product take-back, disassembly, or WEEE compliance programs? |
| **LCA/PCR Experts** | 1. Is a phased approach using TM65 leading toward full EPDs a practical strategy for residential equipment?<br>2. What is the trajectory for improving embodied carbon data availability for residential equipment?<br>3. What are the risks and opportunities for manufacturers in developing and reporting equipment life span data?<br>4. Do you have suggestions for improving data quality management, PCR development, or other opportunities to strengthen embodied carbon reporting?<br>5. What is your overall reaction to the proposed framework for integrating embodied carbon, refrigerant, and life span impacts into standards?<br>6. Could TM65 be adapted for electrical and electronic equipment (EEE)? If not, should it be expanded? |

| Stakeholder Category | Questions |
|---|---|
| **Practitioners** | 1. How common is refrigerant leakage in the field? How difficult is it to test and commission systems to avoid leakage? Are leak monitoring and third-party commissioning seen as benefits or liabilities?<br>2. How would having embodied carbon and expected life span information for residential equipment affect your work? What would be the benefits or challenges?<br>3. Would contractors participate in refurbishment, repair, or end-of-life management (Value Retention Processes)? What are the opportunities or challenges?<br>4. What is the impact of shortened product life spans on contractors and customers? Is it a benefit, liability, or neutral?<br>5. Should embodied carbon and life span be brought into equipment performance standards, installation practices, or mechanical codes? Any other contractor perspectives to consider? |
| **Policy Experts** | 1. What role should standards development play in broader embodied carbon (EC) policy work? How can it better align with policy and incentive efforts?<br>2. What is the trajectory for including residential equipment (MEP, appliances, electronics) in embodied carbon policy? What is happening now, and what is needed?<br>3. How is life span and premature obsolescence showing up in policy? Are there circularity efforts gaining traction in standards, policy, or incentives?<br>4. What are your insights on improving data development, data quality, or PCR development for residential equipment? |
| **Standards Experts** | 1. Are there existing standards that address end-of-life management or disposal of products?<br>2. Can standards meaningfully address end-of-life considerations? If so, how?<br>3. Are there opportunities to address post-installation periods within standards? Are there existing standards or programs around recycling?<br>4. Can you provide an overview of standards types, hierarchies, dependencies, and any missing categories?<br>5. What are the similarities and differences in developing standards across different equipment types (e.g., stakeholders, friction points, priorities)?<br>6. Are there strengths or weaknesses in the current standards hierarchy and the areas we are focusing on? |

# Appendix D – EPDs/LCAs/PCRs for Equipment in Scope

| Equipment Category | EPDs Available | PCRs Available | PEPs Available | LCAs Available | Other |
|---|---|---|---|---|---|
| **Water Heating Systems (Electric)** | Limited (EU only) | None | None | Some (EU-focused) | |
| **Water Heating Systems (Gas)** | Limited (EU only) | None | None | Some (EU-focused) | |
| **Glass Storage Tanks** | Limited (EU only) | None | None | Some (EU-focused) | |
| **Refrigerators** | 1 (Norwegian) | None | None | 1 Norwegian LCA | Sustainability Standard |
| **Freezers** | None | None | None | None | Sustainability Standard |
| **Wine Chillers** | None | None | None | None | |
| **Electric Ranges** | None | None | None | None | Sustainability Standard |
| **Clothes Washers** | None | None | None | | Sustainability Standard. 1 LCA reported (Midea, unverified) |
| **Dishwashers** | None | None | None | 2 (Limited embodied carbon focus) | |
| **Room/Portable Air Conditioners** | None | None | None | 1 student LCA (not third-party reviewed) | |
| **Air Handling Units** | Several (EU-based) | | 2 PEPs | | |
| **Fan Coils** | Several | | Several | | |
| **Motors and Pumps** | 5 EPDs | | 4 PEPs | | |
| **Heat Pumps** | Numerous (EU-based, some NA) | | Few (EU-based) | | |
| **Energy Recovery Ventilators (ERVs)** | Limited (EU only) | | | | |

| Equipment Category | EPDs Available | PCRs Available | PEPs Available | LCAs Available | Other |
|---|---|---|---|---|---|
| **Dehumidifiers** | None | None | None | None | |
| **Humidifiers** | None | None | None | None | Sustainability Standard (limited) |
| **Microwaves** | None | None | None | 1 LCA (not verified) | |
| **Thermostats** | 2 EPD | Limited | None | 1 LCA (not in zotero) | |
| **Set-Top Boxes** | None | None | None | 1 LCA (limited) | |
| **Networking Equipment** | None | None | None | Limited | |
| **Televisions (TVs)** | None | None | None | A few LCAs | |
| **Displays** | Yes | None | None | 1 manufacturer-focused | "1 additional data source" |
| **Cables, Connectors, and Wires** | Several | | Yes | | |
| **Electronic and Electric Equipment** | Several | Yes | None | | Declare Label |
| **Battery Charging Systems** | Data is confined to residential whole-house inverters and utility and commercial scales; no residential-scale information is available. | | | | |
| **Ceiling Fans** | None | None | None | None | |
| **Drinking Water Systems** | None | A few (non-residential) | None | None | |

# Appendix E – Full Standards Development Framework

## E.1 Embodied Carbon Emissions Framework

### Embodied Carbon Emissions:
### Standards Integration Strategy

**Create New Standards**

| **Phase One:** Create residential whole building emissions standards, develop technical specifications around equipment emissions calculations, support PCR/EEE resource development |
|---|
| **New Standard:** Residential Whole Building Embodied Carbon Evaluation Standard<br>**Standards Alignment:** RESNET/ANSI/ICC Standard 1550 (in development)<br>**Imperative:** Creates reporting standard within which equipment emissions ca be reported. Include national guidelines on wbLCA assumptions (e.g. refrigerant leakage rates, RSLs) relevant to residential equipment. |
| **New Standard:** Equipment PCR Development<br>**Standards Alignment:** ISO/CSA 14000 series<br>**Imperative:** Establish PCRs for equipment scope; Binational initiatives for MEP PCR currently in development |
| **New Technical Specification:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology<br>**Standards Alignment:** ASHRAE TM65NA<br>**Imperative:** Establish a calculation methodology using TM65NA Basic immediately, TM65 NA Mid-Level in near term, Type III EPDs to follow; this establishes consistent reference service life data |
| **New Technical Specification:** EEE Embodied Carbon Emissions Calculation Methodology Development Guidance<br>**Standards Alignment:** ASHRAE TM65NA<br>**Imperative:** Provide guidance and resources on how to adapt TM65NA methodology for EEE |
| **New Technical Specification:** Alignment of Energy Efficiency and Life Cycle Emission Strategic Development<br>**Standards Alignment:** CSA Efficiency Standards, 1550, Canada Green Buildings Strategy, ASHRAE TM65NA<br>**Imperative:** Provide guidance on how to coordinate energy efficiency and life cycle emission standards |

**Phase Two:**
Establish emissions standards and technical specifications, benchmarking methodology, and begin reporting emissions within existing standards



**Create New Standards**

**New Standard:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Standards Alignment:** ASHRAE TM65NA

**Imperative:** Update TM65NA Basic Tech Spec to require TM65NA Mid-Level Standard, Type III EPDs to follow

**Standards Modification:** Equipment Construction and Performance Standards (e.g. CSA C22.2 NO. 60335-2-40:221

**Standards Alignment:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Imperative:** Require reporting of TM65NA emissions for equipment within scope in normative body of standard



**Substantial Updates to Existing Standards**

**New Technical Specification:** Equipment Embodied Carbon Emissions Benchmarking Methodology

**Standards Alignment:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Imperative:** Establish new benchmarking methodology based on adapted TM65NA reporting

**New Technical Specification:** EEE Equipment Embodied Carbon Emissions Calculation Methodology

**Standards Alignment:** EEE Embodied Carbon Emissions Calculation Methodology Development Guidance

**Imperative:** Establish new EEE GWP calculation methodology based on TM65NA methodology



**Substantial Updates to Existing Standards**

**Phase Three:**
Require EPD development, establish emission limits for equipment

**Standard Modification:** Equipment Embodied Carbon Emissions Calculation Methodology

**Standards Alignment:** ISO 14000 Series

**Imperative:** Requires Type III EPDs for all equipment in scope (may be phased differently for HVAC and EEE)



**Create New Standards**

**New Technical Specification:** Equipment Embodied Carbon Emissions Limit Guidance

**Standards Alignment:** Equipment Embodied Carbon Emissions Benchmarking Methodology

**Imperative:** Provide guidance on appropriate emission limits to be incorporated into equipment standards



**Substantial Updates to Existing Standards**

**Phase Four:**
Begin incorporating emission limits into equipment standards

**Standard Modification:** Equipment Performance Standards (e.g. CAN/CSA-C191-1 3)

**Standards Alignment:** Equipment Embodied Carbon Emissions Calculation Methodology

**Imperative:** Establish a maximum emissions standard for equipment based on benchmarking and analysis from reported data in prior phases in normative body standard

## Phase 1

1. **New Standard: Residential Whole Building Embodied Carbon Evaluation Standard**
   - A national residential-specific standard for conducting and reporting wbLCA will create a structure within which equipment emissions can be reported. This will also standardize important assumptions, such as refrigerant leakage and reference service lives of equipment, which have significant impacts on emission assessments.
2. **New Standard: Equipment PCR Development**
   - Establish PCRs for all equipment in scope. This should be led by an impartial standards organization to ensure multi-stakeholder engagement and coordinate PCR development across the industry. A binational initiative to develop a PCR for mechanical, electrical, and plumbing equipment is currently in development; however, no such initiative is underway for electrical and electronic equipment.
3. **New Standard: HVAC Equipment Embodied Carbon Emissions Calculation Methodology**
   - Establish a Canadian-specific adoption of the ASHRAE TM65NA Basic Calculation as a technical specification to encourage immediate assessment and reporting of HVAC equipment embodied carbon emissions. This is a precursor towards a Phase Two action to use TM65NA Mid-Level Calculation as a calculation and reporting standard, which will provide a functional methodology in anticipation of a longer period of time before sufficient PCRs and EPDs are developed to become the basis of future reporting for equipment.
4. **New Technical Specification: Electrical and Electronic Equipment Embodied Carbon Emissions Calculation Methodology Development Guidance**
   - Develop a technical standard to explore the expansion of TM65NA methodology to cover electrical and electronic equipment to ensure all equipment in scope has a consistent methodology for preliminary embodied carbon assessment and reporting, pending the longer-term development of a robust PCR and EPD data ecosystem.
5. **New Technical Specification: Alignment of Energy Efficiency and Life-Cycle Emission Strategic Development**
   - Develop a technical specification to research the nexus between energy efficiency and embodied carbon reduction strategies and provide guidance on how to coordinate energy efficiency and life-cycle emission reduction standards.

## Phase 2

1. **New Standard: HVAC Equipment Embodied Carbon Emissions Calculation Methodology**
   - After an initial roll-out of TM65NA Basic Calculation as a technical specification in Phase One, this standard would increase the calculation rigor to Mid-Level Calculation. Implementing the practice as a standard will provide consistency with the anticipation of a longer period of time before sufficient PCRs and EPDs are developed to become the basis of future reporting for equipment.
2. **Standard Modification: Equipment Performance Standards (e.g., CSA C22.2 NO. 60335-2-40:22)**
   - Results from TM65NA analysis would be required to be declared as a component of performance requirements for equipment. The establishment of a national dataset of TM65NA values for equipment in scope to be used as default values when product-level TM65NA values are not provided could be provided by a Phase One technical specification for manufacturers unable or unwilling to provide product-level information.
   - This would allow for consistent embodied carbon data collection for equipment in scope, greatly informing embodied carbon reduction strategies and enabling wbLCA analysis inclusive of this equipment.
   - This declaration should be incorporated into the normative body of the standards; however, the standards development committee may elect to first implement this content into a standards annex.

3. **New Technical Specification: Equipment Embodied Carbon Emissions Benchmarking Methodology**
    - As the dataset of equipment embodied carbon emissions grows through the implementation of TM65NA reporting through equipment performance standards, a methodology for conducting benchmarking of typical emissions for equipment in scope can be established to govern how to identify median values and outliers for equipment within a particular category.
    - The intention of creating this benchmarking methodology will be to facilitate research to inform prescribing emission limits in future phases.
4. **New Technical Specification: Electrical and Electronic Equipment Embodied Carbon Emissions Calculation Methodology**
    - Pending the development of a technical standard to explore the expansion of TM65 methodology to cover electrical and electronic equipment in Phase One, this technical specification will codify TM65NA Basic Calculation for Electrical and Electronic Equipment, and provide a basis for which policy can direct implementation.

## Phase 3

1. **Standard Modification: Equipment Embodied Carbon Emissions Calculation Methodology**
    - Once there has been sufficient development of Type III EPDs to represent equipment in scope, the prior standards requiring TM65NA Mid-Level Calculations would be updated to require EPDs for reporting purposes. In that it is unpredictable as to how data development for electrical and electronic will proceed, this modification may need to be conducted first for MEP equipment, with electrical and electronic equipment to follow.
2. **New Technical Specification: Equipment Embodied Carbon Emissions Limit Guidance**
    - Having established a methodology for conducting benchmark analysis on equipment embodied carbon emissions in Phase Two, this technical specification would provide a research-based evaluation of an appropriate limit of embodied carbon emissions for equipment in scope.
    - The intention of this technical specification is to create a data-driven basis from which embodied carbon emission limits can be incorporated into performance standards in the next phase.

## Phase 4

1. **Standard Modification: Equipment Performance Standards (e.g., CSA C22.2 NO. 60335-2-40:22)**
    - Having established reasonable upper limits of embodied carbon emissions for equipment, these limits would then be incorporated into performance standards for said equipment.
    - These limits should be incorporated into the normative body of the standards; however, the standards development committee may elect to first implement this content into a standards annex.

## E.2 Refrigerant and Gas Emissions Framework

# Refrigerant and Gas Emissions:
## Standards Integration Strategy

**Phase One:**
Establish best practices for refrigerant management and maximum leakage rates



**Create New Standards**

**New Technical Specifications:** Maximum Refrigerant Leakage Rates and Management Practices

**Standards Alignment:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Imperative:** Establish assumed and maximum leakage rates and required associated management practices

**Phase Two:**
Revise existing standards to address emissions, reporting for declared emissions



**Minor Updates to Existing Standards**

**Standard Modification:** CSA B52:73 Mechanical Refrigeration Code; CSA C22.2 No. 120:13, Refrigeration equipment; CSA 8149.1:20 - Natural gas and propane installation code

**Standards Alignment:** Environmental Code Of Practice for the elimination of fluorocarbon emissions from refrigeration and air conditioning systems (ECCC 2021); HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Imperative:** Update current refrigerant and gas management standards to ensure protocols for leakage, capture, disposal are aligned with best practices for GHG emission avoidance



**Substantial Updates to Existing Standards**

**Standard Modification:** Equipment Performance Standards (e.g. CSA C22.2 NO. 60335-2-40:22)

**Standards Alignment:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology; RESNET/ANSI Standard 1550 (in development)

**Imperative:** Update current refrigerant- and gas-based equipment performance standards to require declaration of GWP specific to refrigerant- and gas-based emissions

**Standard Modification:** Equipment Performance Standards (e.g. CSA C22.2 NO. 60335-2-40:22)

**Standards Alignment:** Maximum Refrigerant Leakage Rates and Management Practices

**Imperative:** Confirm sufficient guidance for leakage management in product Installation manuals



**Create New Standards**

**Phase Three:**
Establish emissions limits for residential equipment

**New Technical Specification:** Refrigerant and Gas Emissions Limits for Residential Equipment

**Standards Alignment:** Equipment Embodied Carbon Emissions Benchmarking Methodology, Equipment Embodied Carbon Emissions Limit Guidance

**Imperative:** Establish fugitive emission limits for all residential equipment through entire product life cycle in coordination with broader embodied carbon benchmarking and emission limits



**Substantial Updates to Existing Standards**

**Phase Four:**
Incorporate emission limits into equipment standards

**Standard Modification:** Equipment Performance Standards (e.g. CSA C22.2 NO. 60335-2-40:22)

**Standards Alignment:** Equipment Embodied Carbon Emissions Calculation Methodology, Refrigerant and Gas Emissions Limits for Residential Equipment

**Imperative:** Update current refrigerant- and gas-based equipment performance standards to declare a maximum GWP specific to refrigerant- and gas-based emissions.

## Phase 1

1. **New Technical Specification: Maximum Refrigerant Leakage Rates and Management Practices**
   - Given the acute risk of fugitive refrigerant emissions from heat pumps, which are increasing in adoption in the residential market, this technical specification will formalize allowable leakage rates for residential refrigerant-based systems and provide guidance on best practices for leakage management. It would also codify a national standard of assumed refrigerant leakage rates to bring consistency to fugitive emission assessments.
   - The scope of this specification should cover all life-cycle stages, including manufacturing, installation, use, and end-of-life decommissioning and disposal. The reporting should similarly be disaggregated by life-cycle stage, such that manufacturers are only responsible for the leakage limits within product development, and installation contracts are only responsible for installation-related leakage.

## Phase 2

1. **Standard Modification: CSA B52:23, *Mechanical Refrigeration Code;* CSA C22.2 No. 120:13, *Refrigeration equipment;* CSA B149.1:20, *Natural gas and propane installation code***
   - Existing standards that address gas and refrigerant leakage for safety considerations should be reviewed to ensure these standards are sufficient to address emissions risk as identified in the technical standard in Phase One.
   - It is expected that gas and propane leakage safety standards are sufficient given the high flammability of these gases; however, refrigerant safety standards are expected to be significantly lower than what is required to manage for emissions risk.
2. **Standard Modification: Equipment Performance Standards (e.g., CSA C22.2 NO. 60335-2-40:22)**
   - Explicit declaration of the GHG emissions associated with refrigerant leakage should be incorporated into refrigerant-based product standards. This could be based on the assumed leakage as defined in the Phase One technical specification.
3. **Standard Modification: Equipment Performance Standards (e.g., CSA C22.2 NO. 60335-2-40:22)**
   - Given that the development of equipment installation and product information manuals fall under the purview of performance standards, these standards should be updated to require sufficient guidance in clarity and scope to manage installation-stage refrigerant leakage.

## Phase 3

1. **New Technical Specification: Refrigerant and Gas Emissions Limits for Residential Equipment**
   - Establish fugitive emission limits for all residential equipment throughout the entire product life cycle in coordination with broader embodied carbon benchmarking and emission limits identified in the Embodied Carbon Emissions Framework.
   - Whereas the Maximum Refrigerant Leakage Rates and Management Practices Technical Standard in Phase One is intended to specifically address leakage rates and management practices, this specification focuses on GHG emissions as a metric and is intended to support more comprehensive emissions reporting that is inclusive of fugitive emissions.

## Phase 4

1. **Standard Modification: Equipment Performance Standards (e.g., CSA C22.2 NO. 60335-2-40:22)**
   - Update current refrigerant- and gas-based equipment performance standards to declare a maximum GWP for a refrigerant system, following the benchmarking research identified in Phases Three and Four in the Embodied Carbon Emissions Framework.
   - The intention of this standard modification is to coordinate with the GHG emissions limits established for equipment, as a coordinated effort to maintain these limits consistently throughout all applicable codes and standards.

## E.3 Equipment Lifespan Framework

# Equipment Lifespan Emissions:
## Standards Integration Strategy

**Create New Standards**

**Phase One:**
Create technical specifications around equipment emission calculations, develop PCR/EEE resource support

**New Standard:** Equipment PCR Development

**Standards Alignment:** ISO/CSA 14000 series

**Imperative:** Establish PCRs for equipment scope; Binational initiative for MEP PCR is in development

**New Technical Specification:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Standards Alignment:** ASHRAE TM65NA

**Imperative:** Establish a calculation methodology using TM65NA Basic immediately, TM65 NA Mid-Level in near term, Type III EPDs to follow; this establishes consistent reference service life data

**New Technical Specification:** EEE Embodied Carbon Emissions Calculation Methodology Development Guidance

**Standards Alignment:** ASHRAE TM65NA

**Imperative:** Provide guidance and resources on how to adapt TM65 methodology for EEE

**Phase Two:**
Establish emission standards and technical specifications, require reporting of equipment service life, establish circularity roadmap



**Create New Standards**

**New Standard:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Standards Alignment:** ASHRAE TM65NA

**Imperative:** Update TM65NA Basic Tech Spec to require TM65NA Mid-Level, Type III EPDs to follow



**Substantial Updates to Existing Standards**

**Standard Modification:** Equipment Performance Standards (e.g. CSA C22.2 NO. 6033S-2-40:22)

**Standards Alignment:** HVAC Equipment Embodied Carbon Emissions Calculation Methodology

**Imperative:** Require reporting of reference service life for equipment in normative body of standard

**New Technical Specification:** EEE Equipment Embodied Carbon Emissions Calculation

**Methodology Standards Alignment:** EEE Embodied Carbon Emissions Calculation Methodology Development Guidance

**Imperative:** Establish new EEE GWP calculation methodology based on TM65NA methodology

**New Technical Specification:** Methodology to Develop Equipment Value Retention Processes

**Standards Alignment:** Equipment Performance and Installation Standards

**Imperative:** Develop a methodology for the evaluation and implementation of value retention processes (reuse, repair, refurbishment, remanufacturing) for equipment.

**Phase Three/Four:**
Implement circularity methodology



**Substantial Updates to Existing Standards**

**Standard Modification:** Equipment Construction and Performance Standards (e.g. CSA C22.2 NO. 60335-2-40:22)

**Standards Alignment:** Methodology to Develop Equipment Value Retention Processes

**Imperative:** Update with requirements for incorporating VRP principles into performance standards



**Create New Standards**

**New Standard:** Standards Related to Value Retention Processes

**Standards Alignment:** Methodology to Develop Equipment Value Retention Processes

**Imperative:** Establish new standards to implement VRPs as outlines in Phase Two technical specification

## Phase 1

1. **New Standard: Equipment PCR Development**
   - This is the same standard as listed in Phase One of the Embodied Carbon Emissions Framework. It is included here as it directly addresses the declaration of reference lifespans within the PRC framework.

2. **New Technical Specification: HVAC Equipment Embodied Carbon Emissions Calculation Methodology**
   - This is the same technical specification as listed in Phase One of the Embodied Carbon Emissions Framework. It is included here as it directly addresses the declaration of reference lifespans within the TM65NA framework.

3. **New Technical Specification: Electrical and Electronic Embodied Carbon Emissions Calculation Methodology Development Guidance**
   - This is the same technical specification as listed in Phase One of the Embodied Carbon Emissions Framework. It is included here as it directly addresses the declaration of reference lifespans within the TM65NA framework.

## Phase 2

1. **New Standard: HVAC Equipment Embodied Carbon Emissions Calculation Methodology**
   - This is the same standard as listed in Phase Two of the Embodied Carbon Emissions Framework. It is included here as it directly addresses the declaration of reference lifespans within the TM65NA framework.

2. **Standard Modification: Equipment Construction and Performance Standards (e.g., CSA C22.2 NO. 60335-2-40:22)**
   - Related to the Standards Modification listed in Phase Two of the Embodied Carbon Emissions Framework, this modification would require the declaration of reference lifespans within the TM65NA framework.
   - This declaration should be incorporated into the normative body of the standards; however, the standards development committee may elect to first implement this content into a standards annex.

3. **New Technical Specification: Electrical and Electronic Equipment Embodied Carbon Emissions Calculation Methodology**
   - This is the same technical specification as listed in Phase Two of the Embodied Carbon Emissions Framework. It is included here as it directly addresses the declaration of reference lifespans within the TM65NA framework.

4. **New Technical Specification: Methodology to Develop Equipment Value Retention Processes**
   - This technical specification is intended to advance development of VRP definitions, procedures, and requirements for the manufacturing process.
   - This technical specification also provides an opportunity to address use-phase repair protocols as they relate to VRP, as well as end-of-life processing opportunities and requirements to fulfill the intent of VRP. Given the current under-regulated nature of end-of-life equipment processing, this technical specification may address the standards and regulatory process of this life-cycle stage in addition to the technical processes of equipment management.

## Phase 3/4

1. **Standard Modification: Equipment Performance Standards (e.g., CAN/CSA-C191-13, *Performance of electric storage tank water heaters for domestic hot water service*)**
    - Once VRP methodologies have been established in Phase Two, equipment performance standards can be modified to include these processes.
    - The standards modifications to declare embodied carbon and reference lifespans referenced in those respective frameworks are of limited impact on the production of the equipment in scope. However, as this would reflect a more substantial change in equipment production, these modifications should first be included as annexes to the standards.
    - It is acknowledged that this may be a multi-phase process depending on the nature of the equipment.
2. **New Standard: Standards Related to Value Retention Processes**
    - Building off the Methodology to Develop Equipment Value Retention Processes Technical Specification in Phase Two, this standard would codify these VRP methodologies into a referenceable standard to guide the implementation of circularity principles across the life-cycle stages for equipment in scope.
    - It is acknowledged that this may be a multi-phase process depending on the nature of the equipment.

## CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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